RECENT RESULTS FROM MINOS AND FUTURE PROSPECTS

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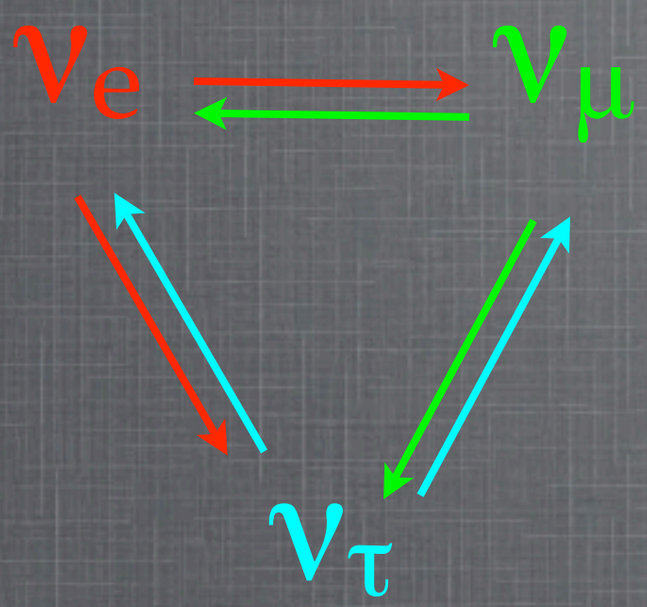
Indiana University

Fermilab Users' Meeting
June 5, 2008

The MINOS Collaboration

Argonne - Arkansas Tech - Athens - Benedictine - Brookhaven - Caltech - Cambridge - Campinas - Fermilab - Harvard - IIT - Indiana - Minnesota-Twin Cities - Minnesota-Duluth - Oxford - Pittsburgh - Rutherford - São Paulo - South Carolina - Stanford - Sussex - Texam A&M - Texas-Austin - Tufts - UCL - Warsaw - William & Mary

Goals of the MINOS Experiment



- Make precise measurement of Δm^2 and $\sin^2(2\theta)$

$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2(2\theta)\sin^2(1.27\,\Delta m^2\,L/E)$$

- Confirm oscillations vs. other explanations (decay, decoherence)

- Secondary goals:
  - Search for subdominant $\nu_\mu \rightarrow \nu_e$
  - Search for sterile neutrinos
  - CPT tests
  - Atmospheric neutrino and cosmic ray studies

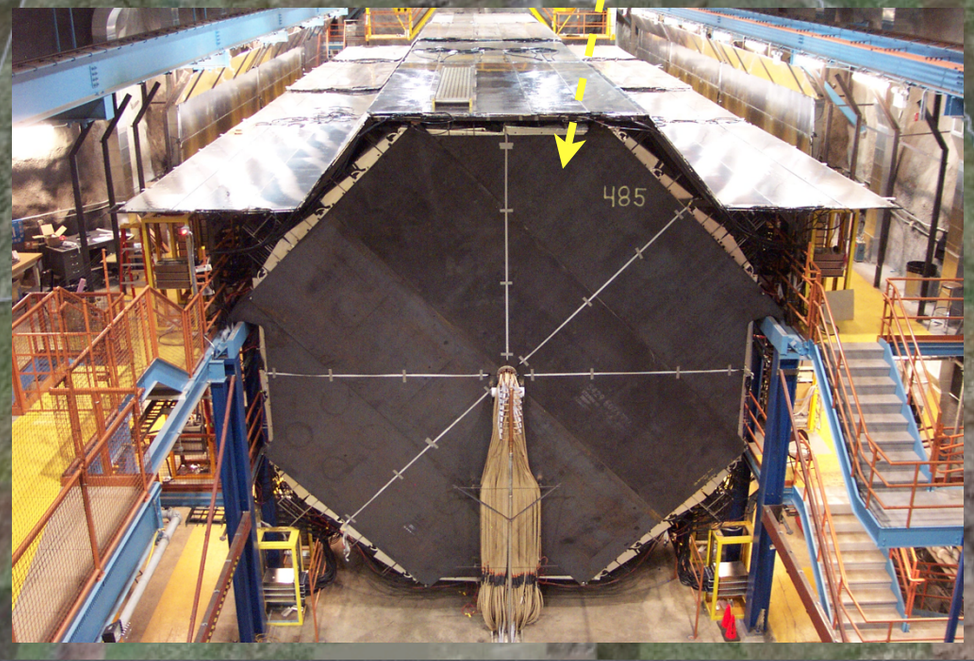
2007-08: Very Productive Year!

- 2 boxes opened (ν_μ CC and NC blind analyses)
- 6 theses
- Significant progress in understanding backgrounds and systematic uncertainties in all analyses

The MINOS Experiment

- Near Detector
  - 0.98 kT
  - 1.04 km from target

- Far Detector
  - 5.4 kT
  - 735 km from target



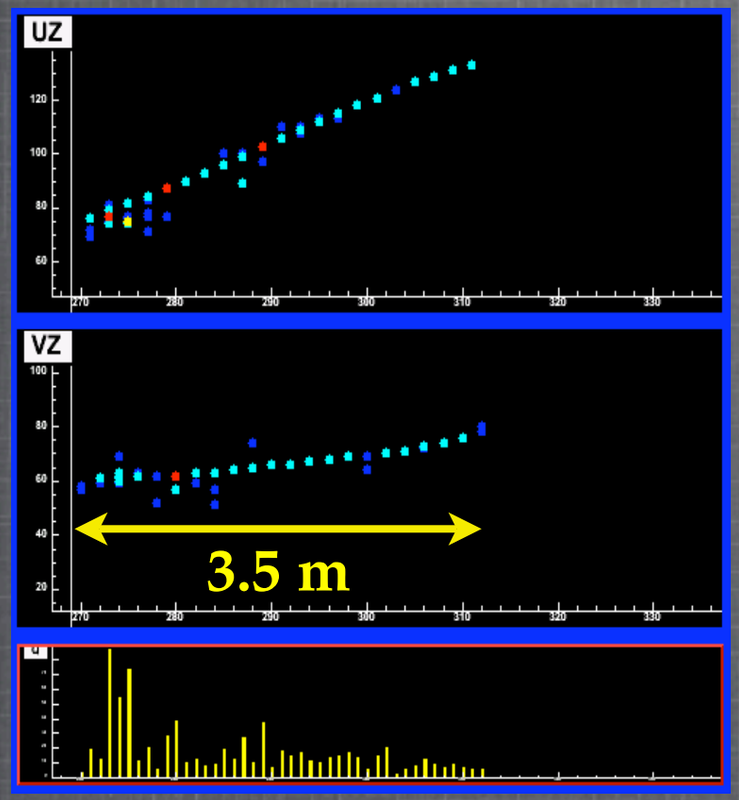
ν_μ beam

735 km

Both detectors are magnetized tracking calorimeters.

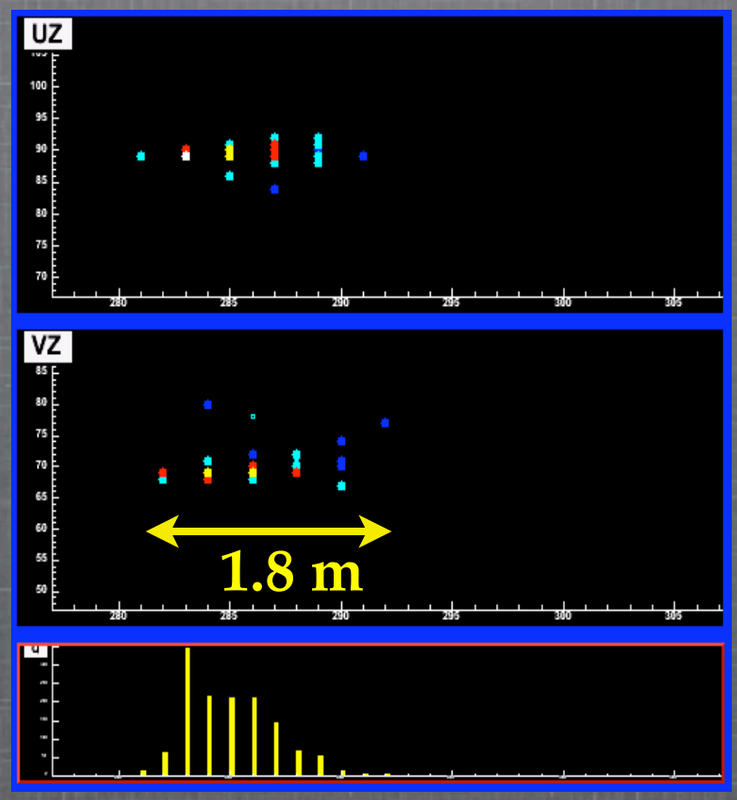
Identifying Events in MINOS

ν_μ CC event



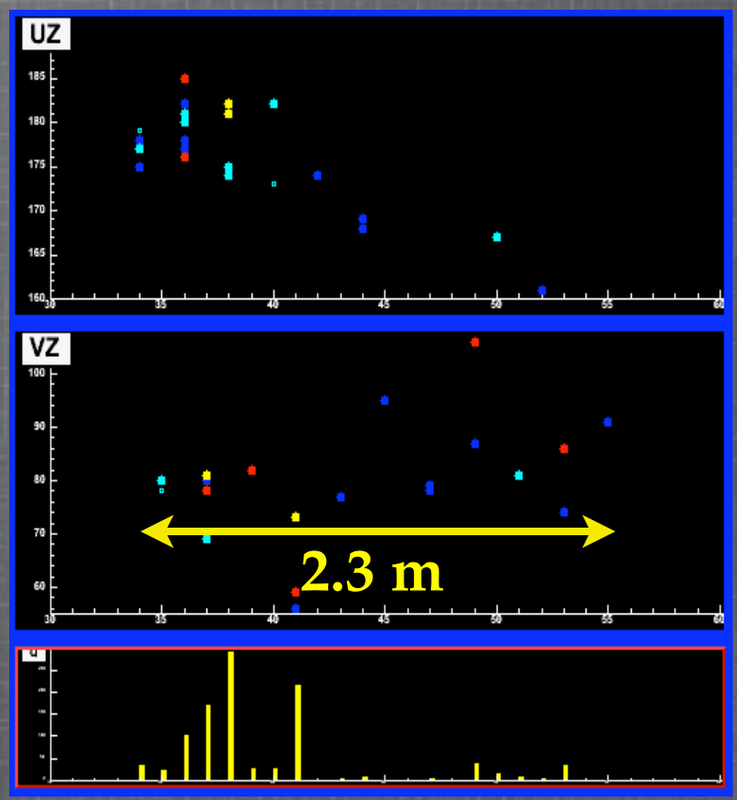
Long μ track + shower at vertex

ν_e CC event



Short event with EM shower profile.

NC event

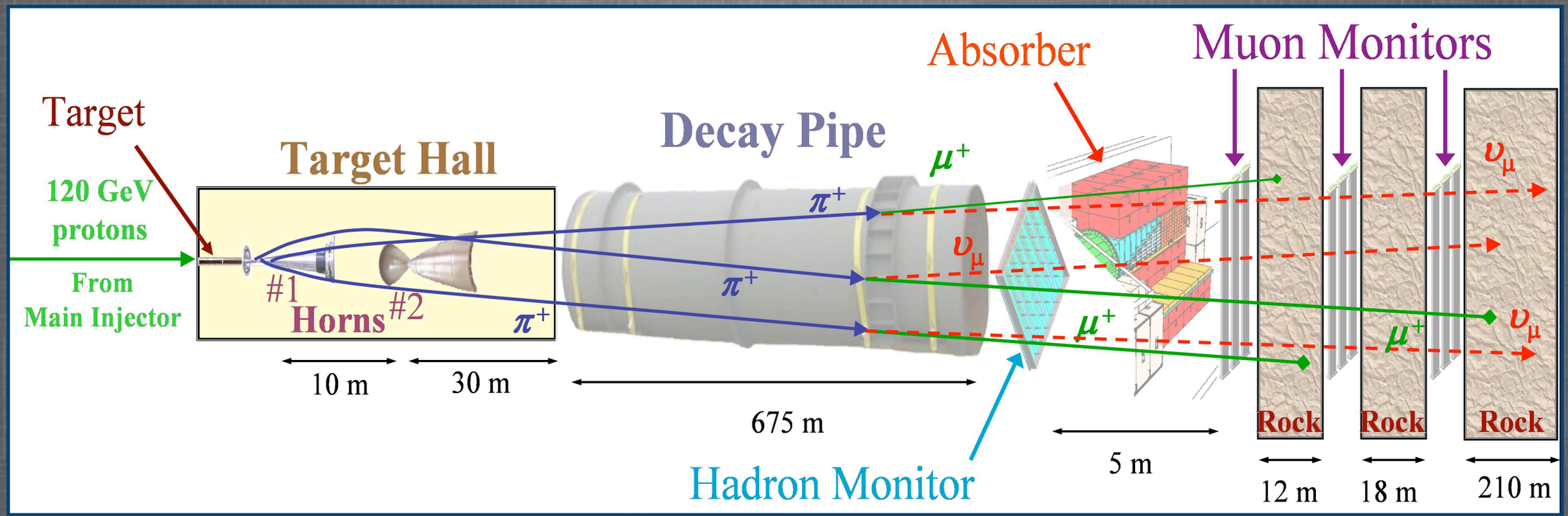


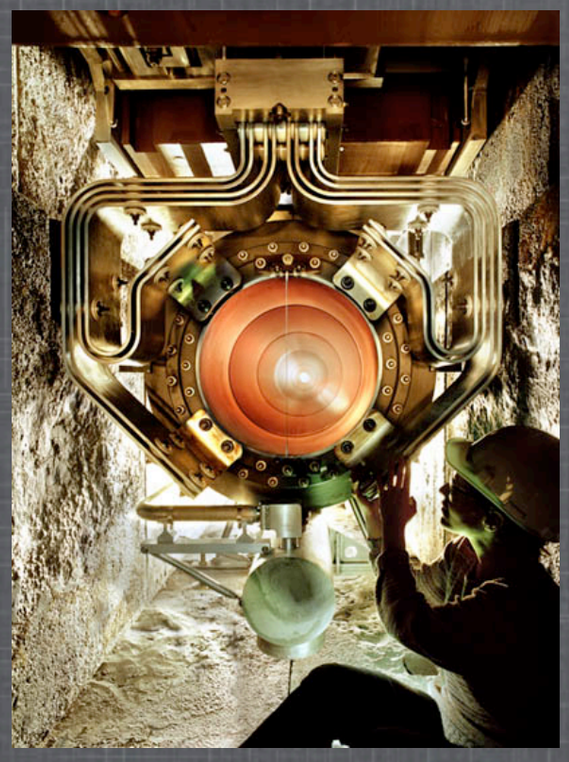
Short, diffuse event.

$$E_\nu = E_{shower} + E_{\mu,e}$$

$\delta E_{shower} = 55\%/\sqrt{E}$ $\delta E_\mu = 6\%$ range, 10% curvature

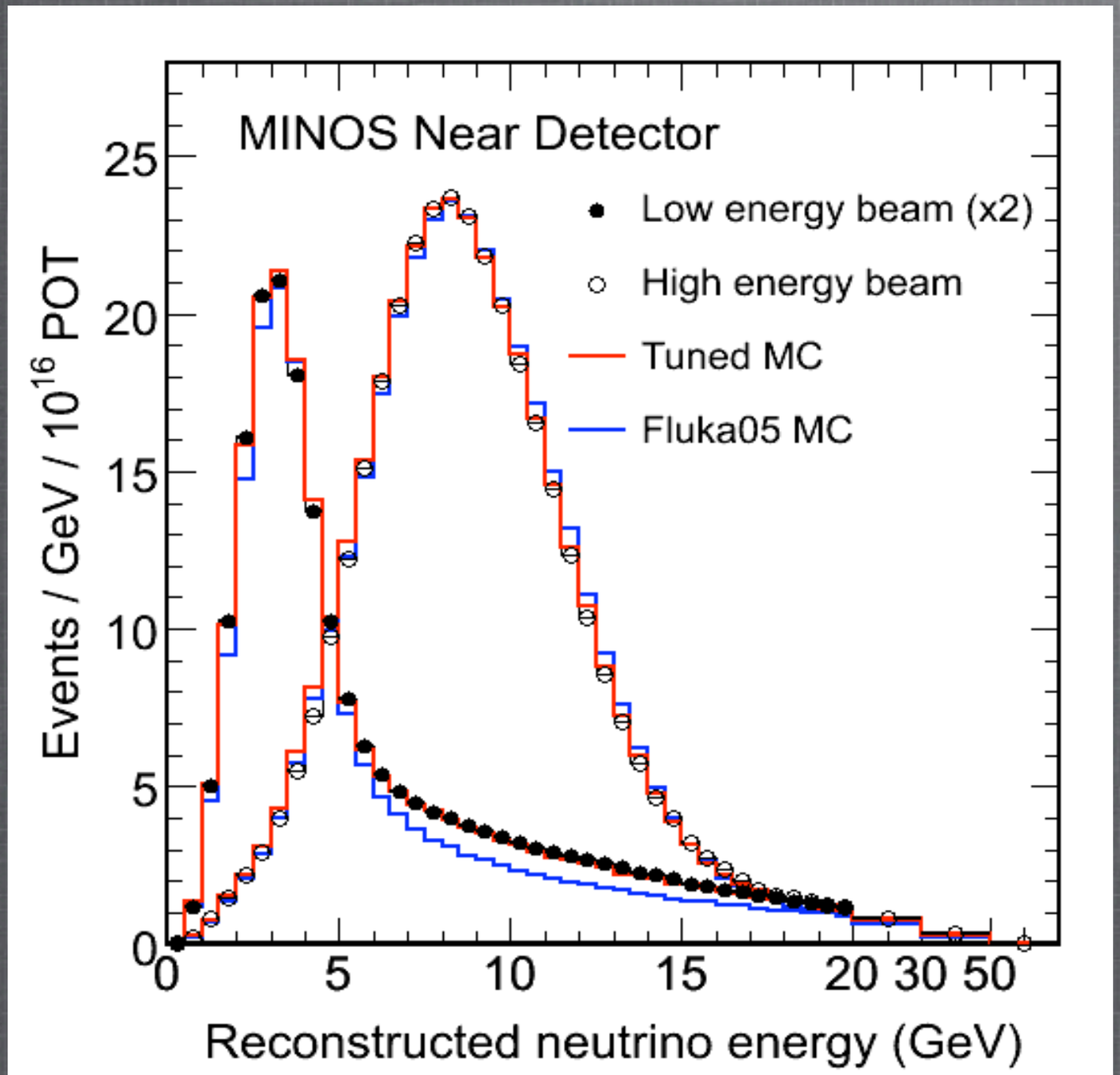
Producing Neutrinos at the Main Injector





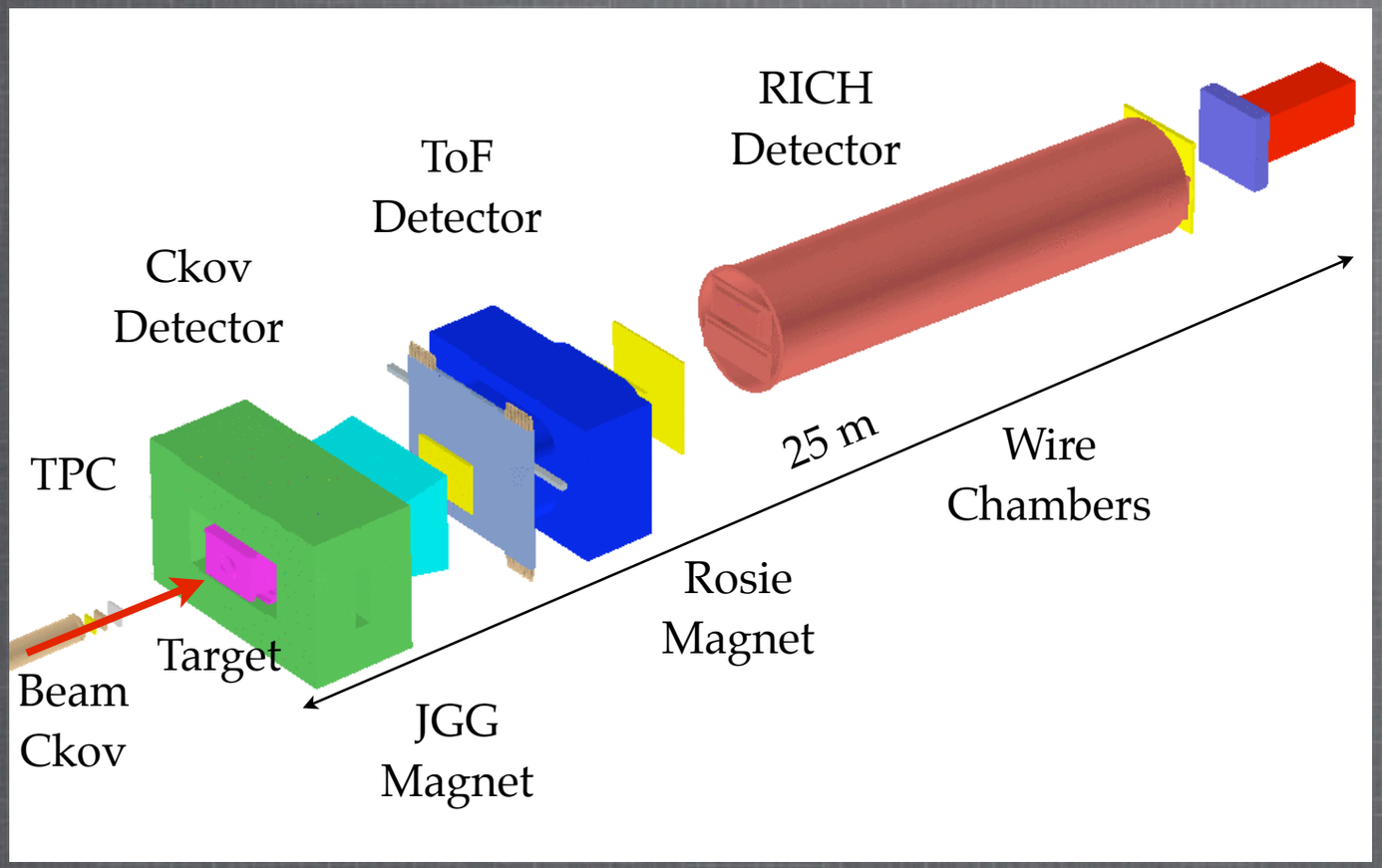
- Mesons produced in 120 GeV/c p + graphite target interactions are focused in two magnetic horns.
- ν beam energy is *tunable* by moving target position longitudinally w.r.t. the horn positions.
- In LE beam configuration, beam is composed of 92.9% ν_μ, 5.8% $\overline{\nu}_\mu$, and 1.3% ν_e and $\overline{\nu}_e$.

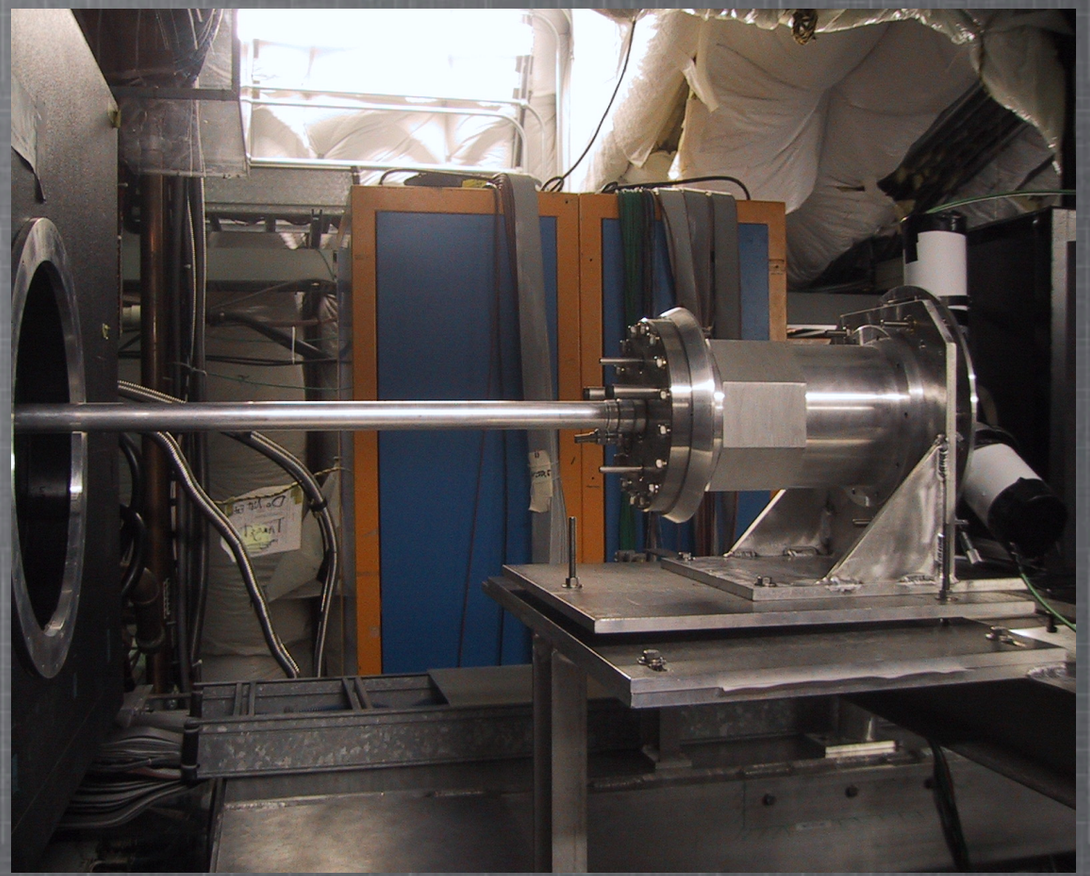
Predicting the Flux



- MINOS uses Fluka06 MC to predict the ν flux.
- Uncertainty on flux is ~30% due to lack of hadron production data.
- To improve our data-to-MC agreement, we tune the Fluka MC to ND energy spectra of different beam configurations.
- These beam-reweighted spectra are used in all analyses discussed today.

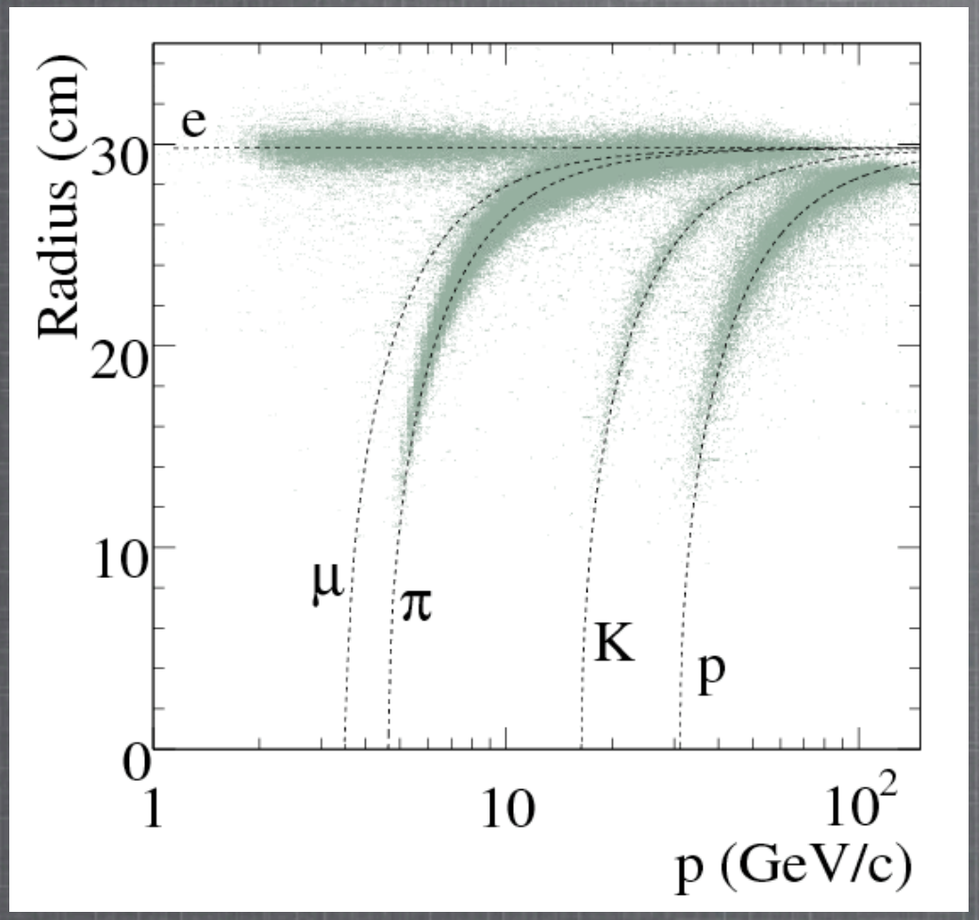
Measurement of Hadron Production off NuMI Target in MIPP

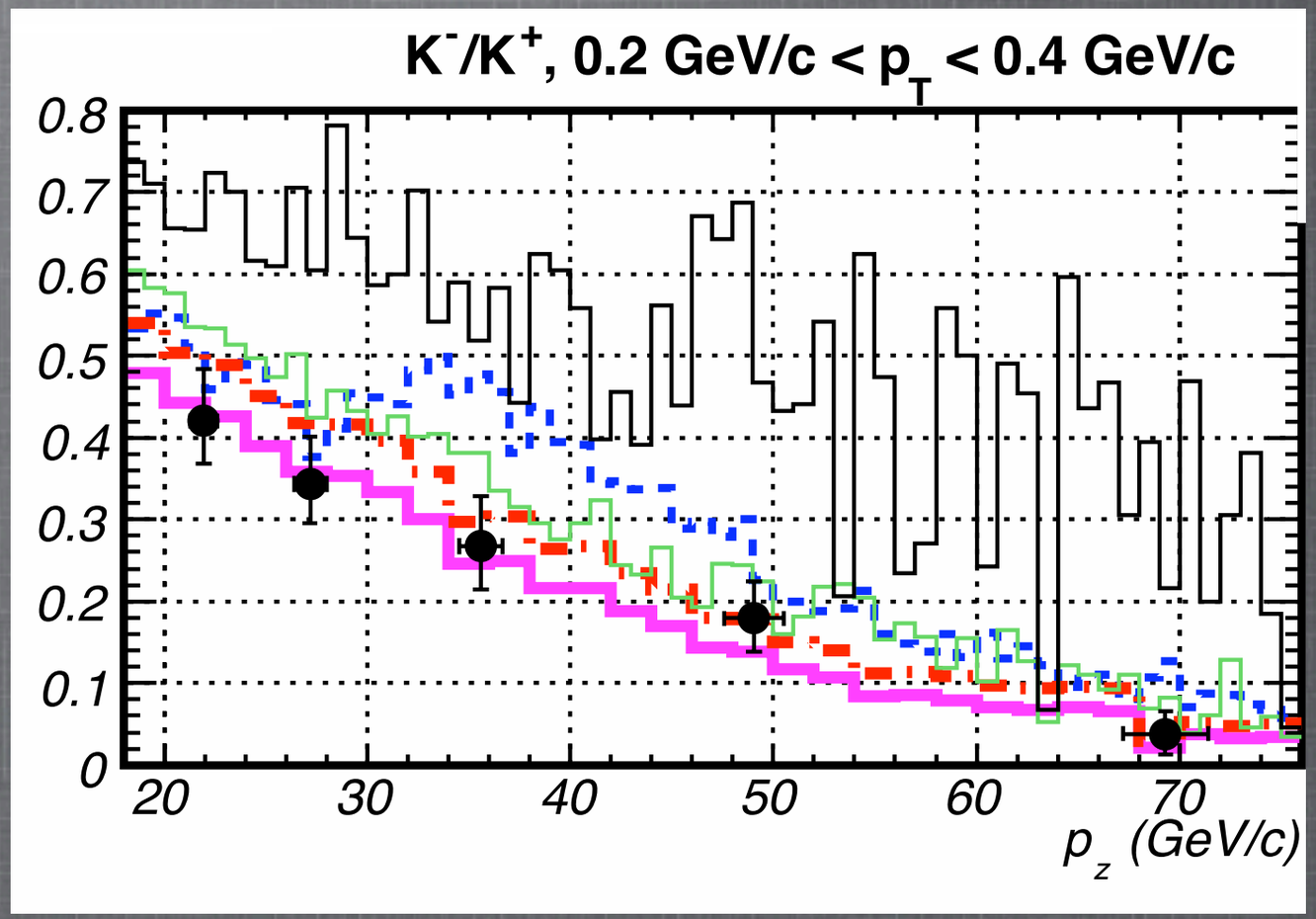




- Main Injector Particle Production (MIPP) is a fixed target experiment with beams of π, K and p from 5-120 GeV/c and LH2, C, Be, Bi, U targets.
- MIPP has collected 1.6 x 10^6 events of 120 GeV p striking the MINOS target.

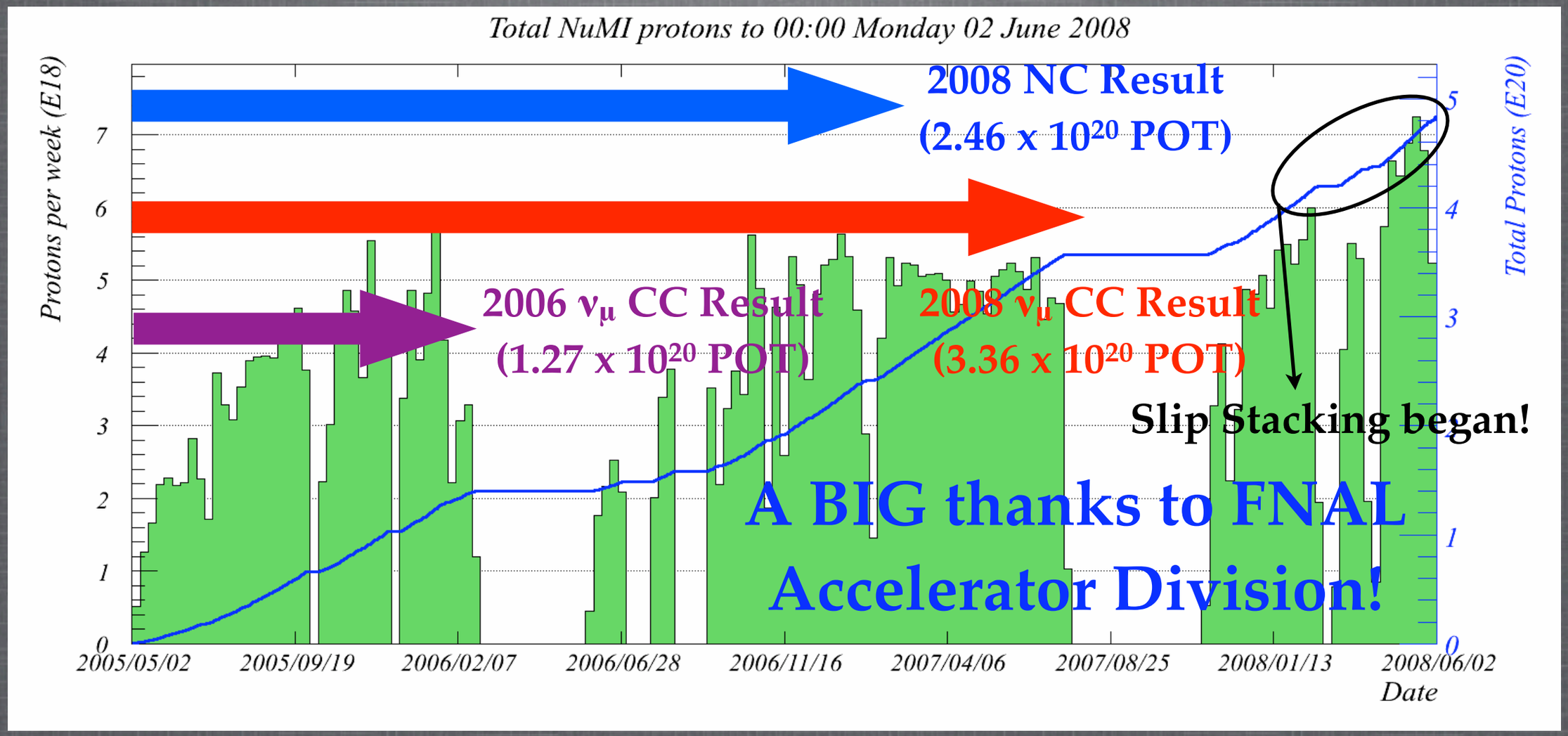
Status of MIPP Analysis





- π^-/π^+, K^-/K^+ , and K/π production ratios above 20 GeV/c agree well with expectations from MINOS beam-tuning.
- The MIPP Collaboration has completed the calibration of all PID detectors and is now focusing on the hadron production measurement from the NuMI target data set.
- See poster by Yusuf Gunaydin.

NuMI Beam



Run I
1.27 x 10^{20} POT

Run II
1.94 x 10^{20} POT

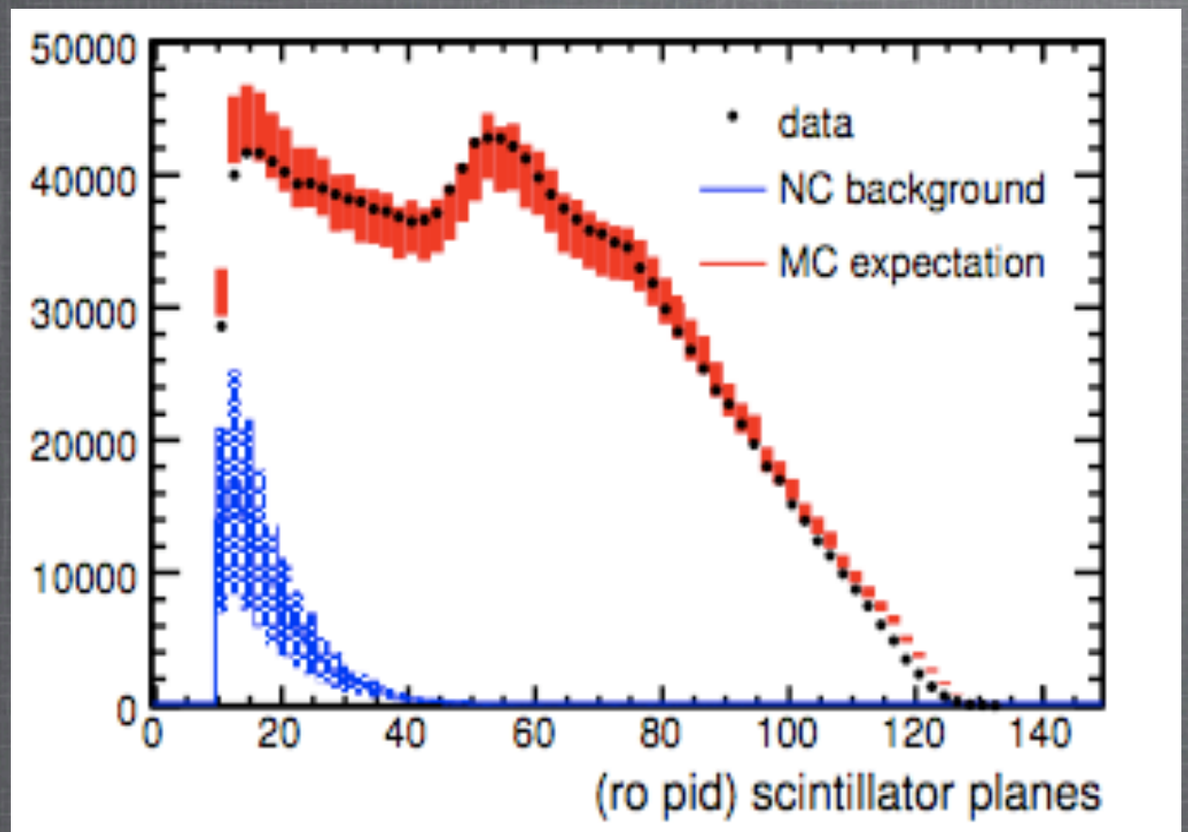
Run III
1.1 x 10^{20} POT

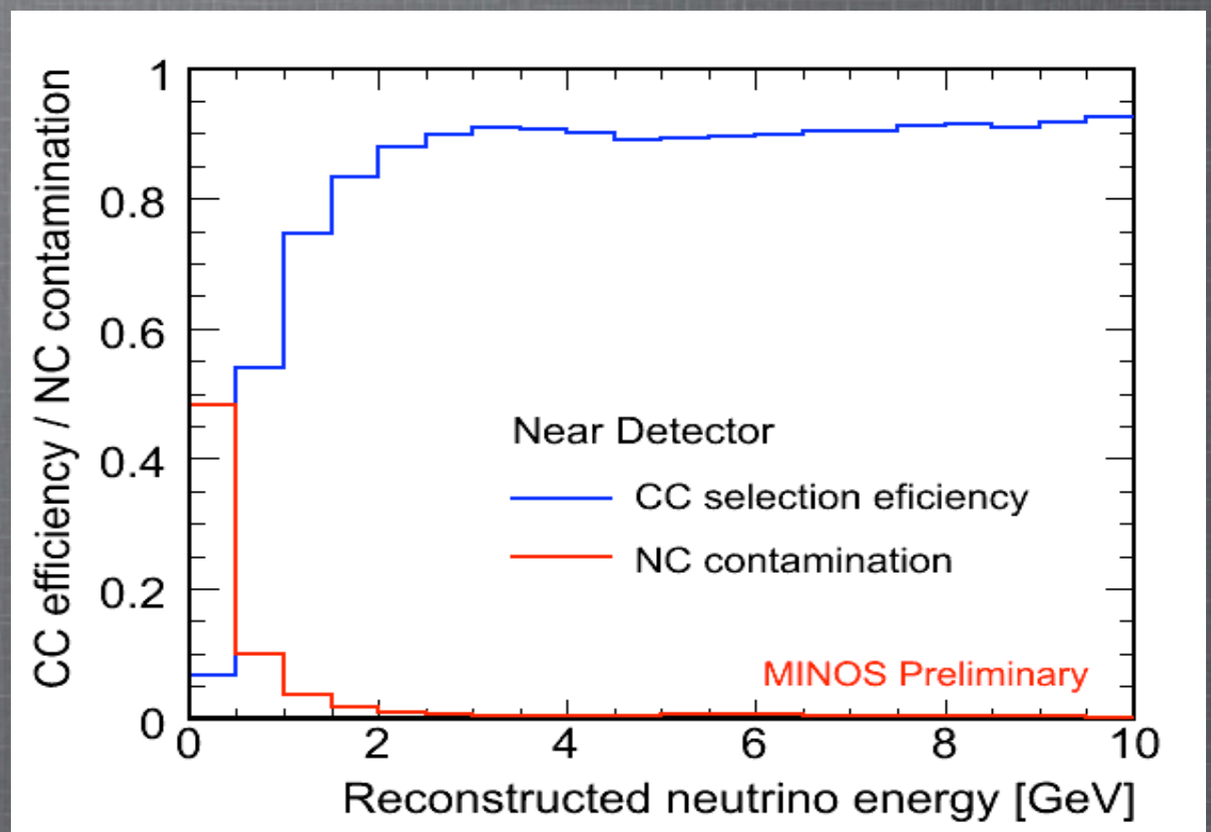
Other beam configurations, including HE beam:
0.15 x 10^{20} POT

ν_μ CC Analysis

Precision measurement of Δm^2 and $\sin^2(2\theta)$

ν_μ CC Event Selection

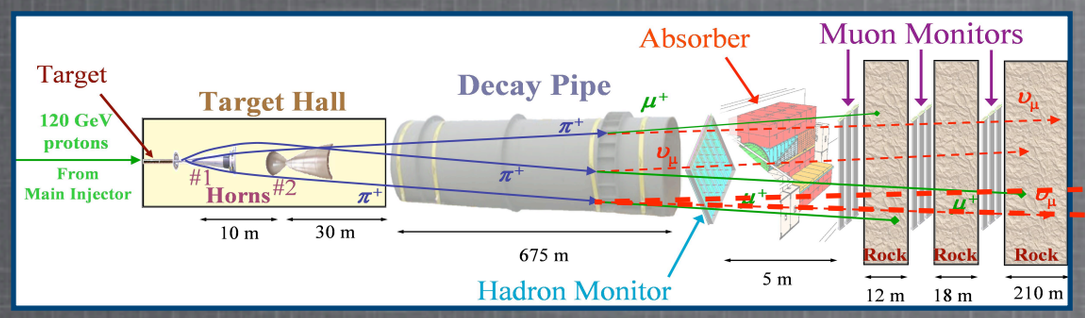




- CC/NC separation achieved via a kNN event selection based on:
  - Track length
  - Mean pulse height
  - Fluctuation in pulse height
  - Transverse track profile

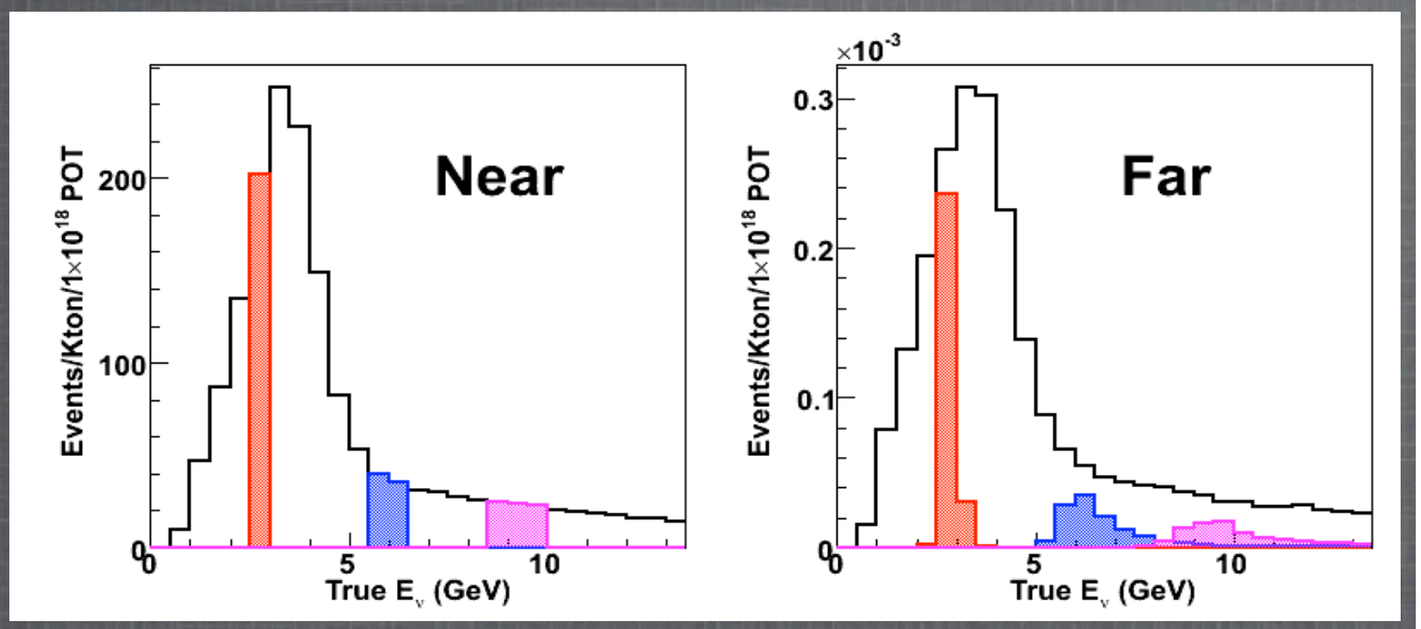
- Cut on separation parameter maximizes CC selection efficiency and minimizes NC background.
- Good agreement between data and MC above the CC/NC separation parameter cut.

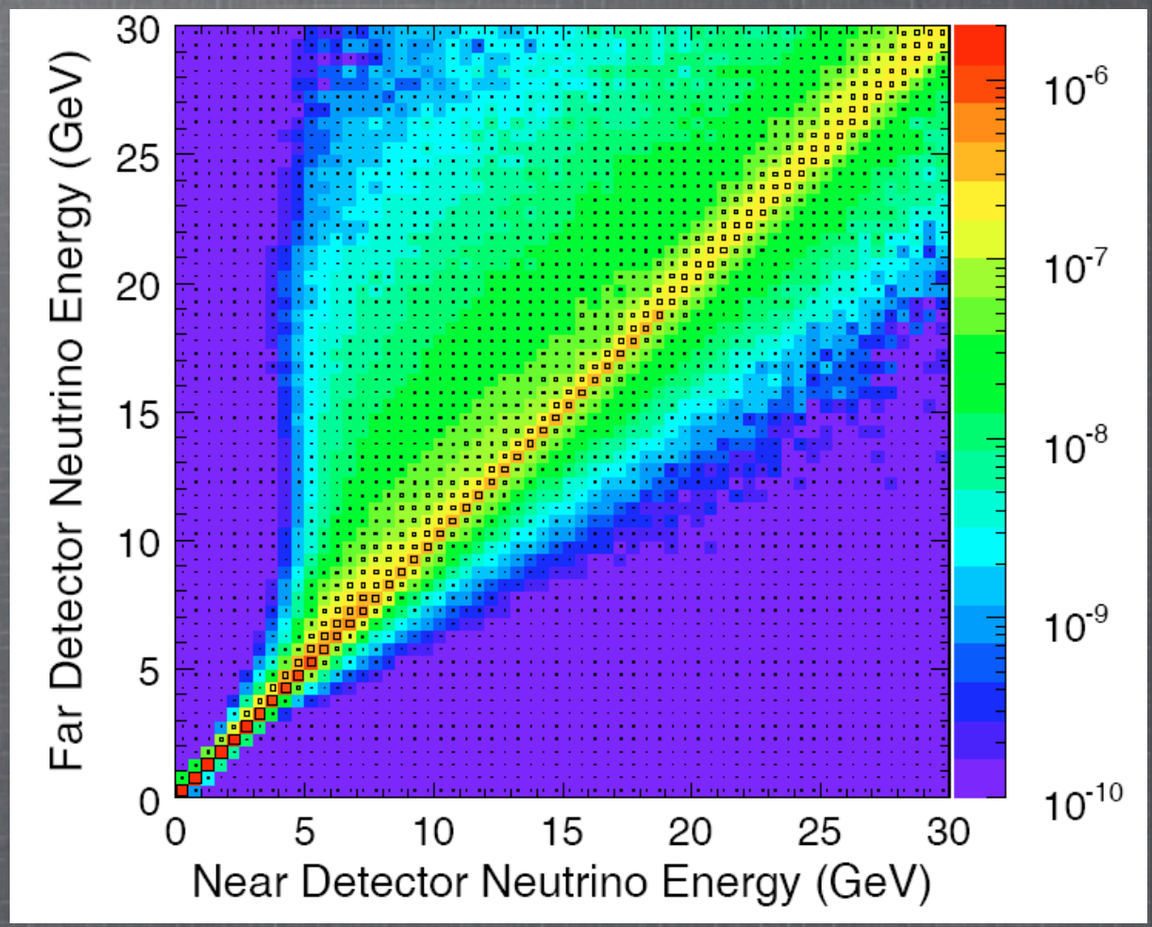
Expected Far Detector Spectrum



Line Source at ND

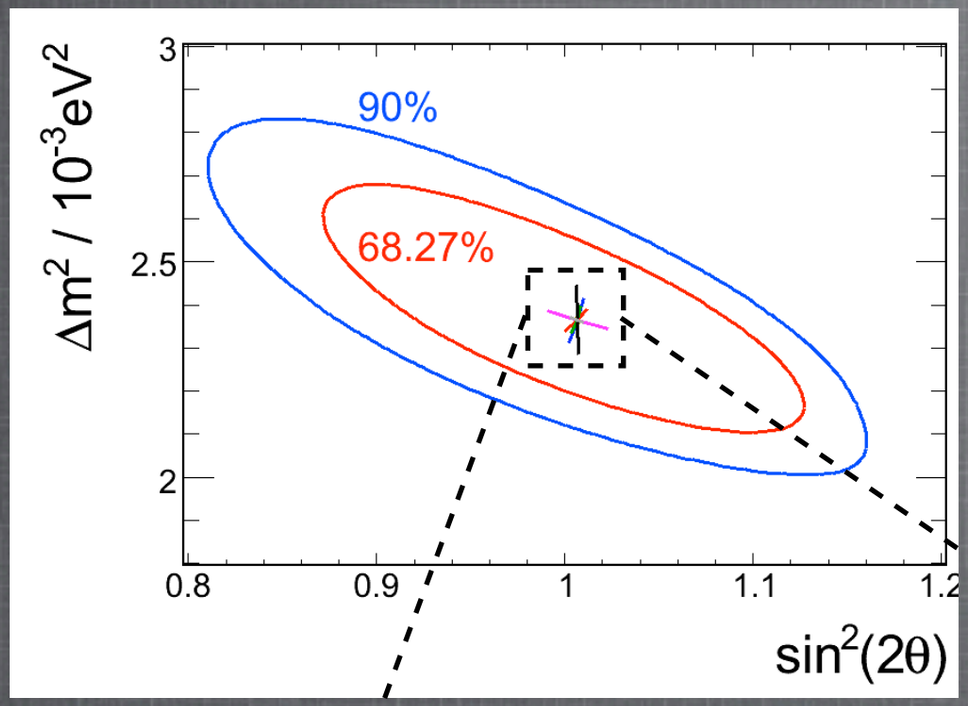
Point Source at FD



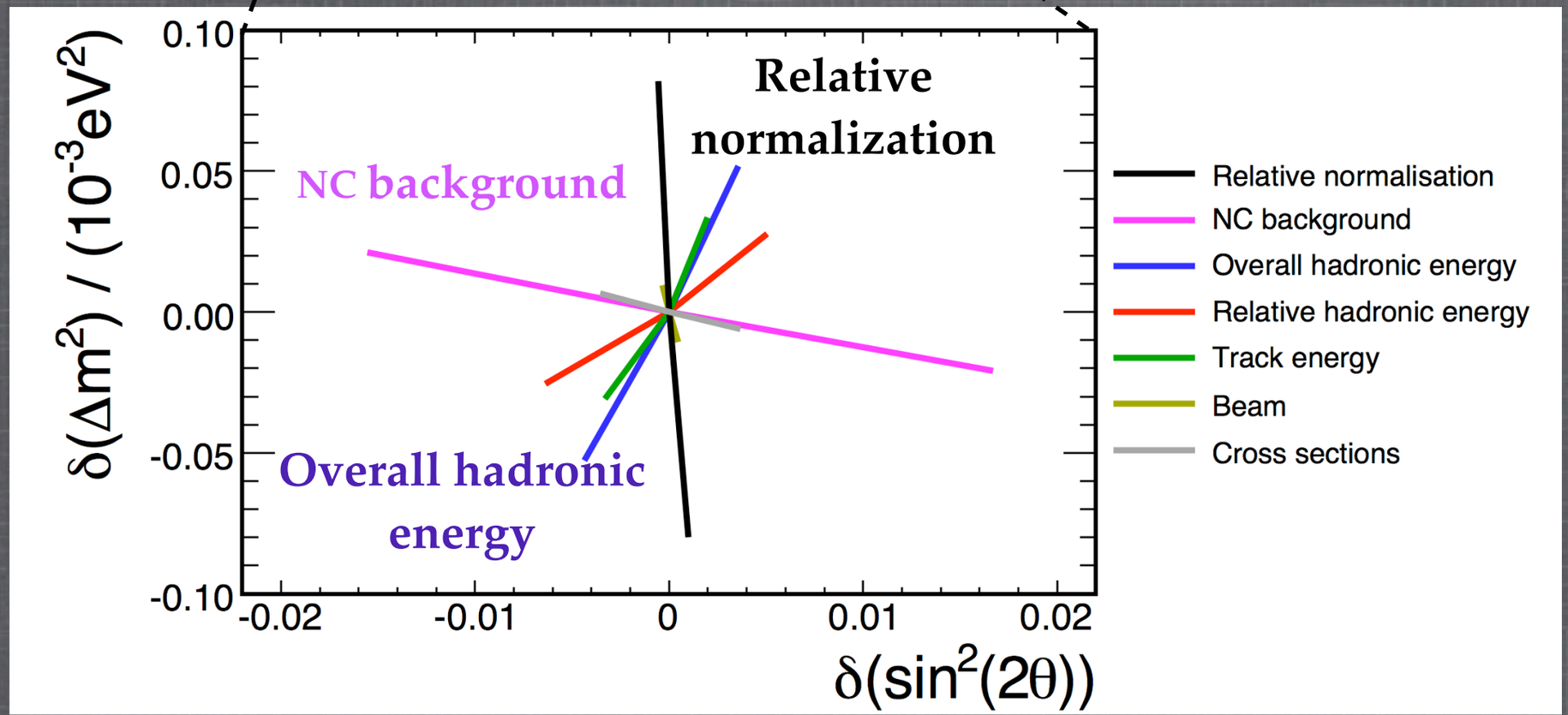


- Near detector spectrum is extrapolated to the far detector.
- Use MC to provide energy smearing and acceptance corrections.

Systematic Uncertainties

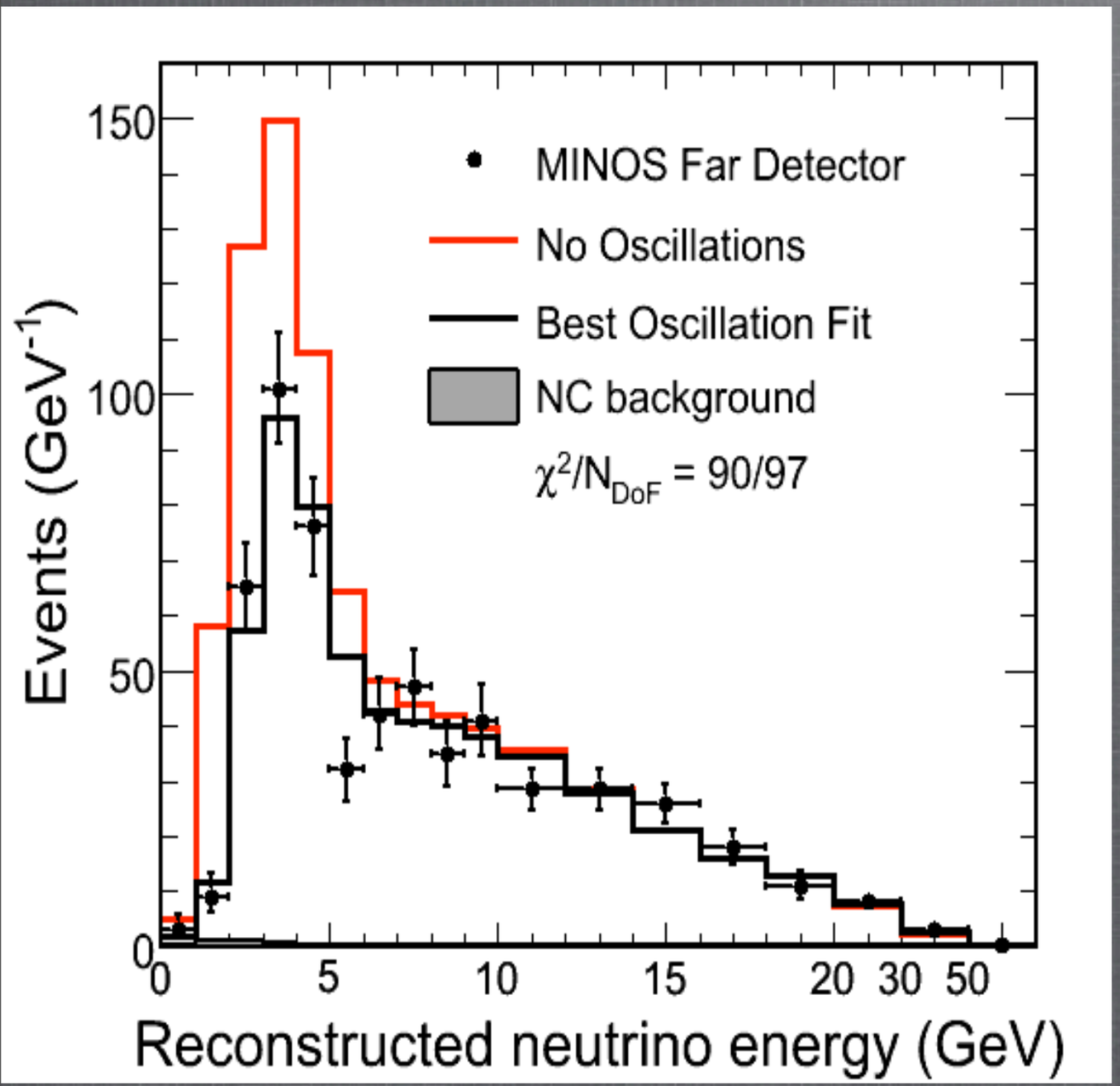


- Systematic uncertainties estimated by fitting modified MC in place of data.
- ν_μ CC measurement is statistics limited.
- Dominant uncertainties are:
  - ND/FD relative normalization (Δm^2)
  - Overall hadronic energy calibration (Δm^2)
  - NC background ($\sin^2(2\theta)$)



- These three systematic effects are included in the final fit as nuisance parameters.

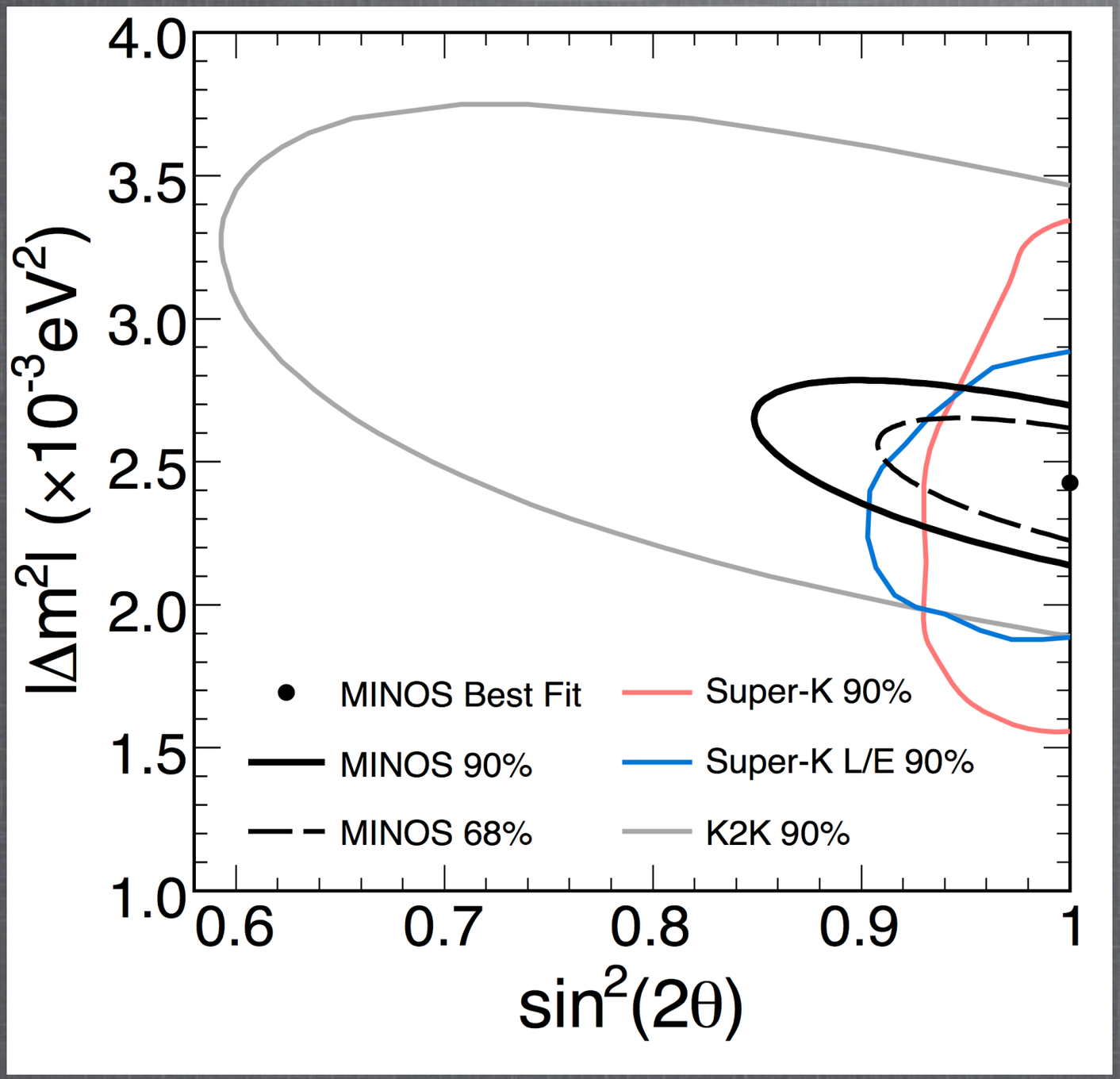
FD Energy Spectrum/Performing the Fit



- FD energy spectrum is only looked at after performing:
  - low-level data quality checks
  - procedural checks
- 848 events observed in the FD
- 1065 ± 60 expected with no oscillations
- We fit the energy distribution to the oscillation hypothesis:

$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2(2\theta)\sin^2(1.27\,\Delta m^2\,L/E)$$

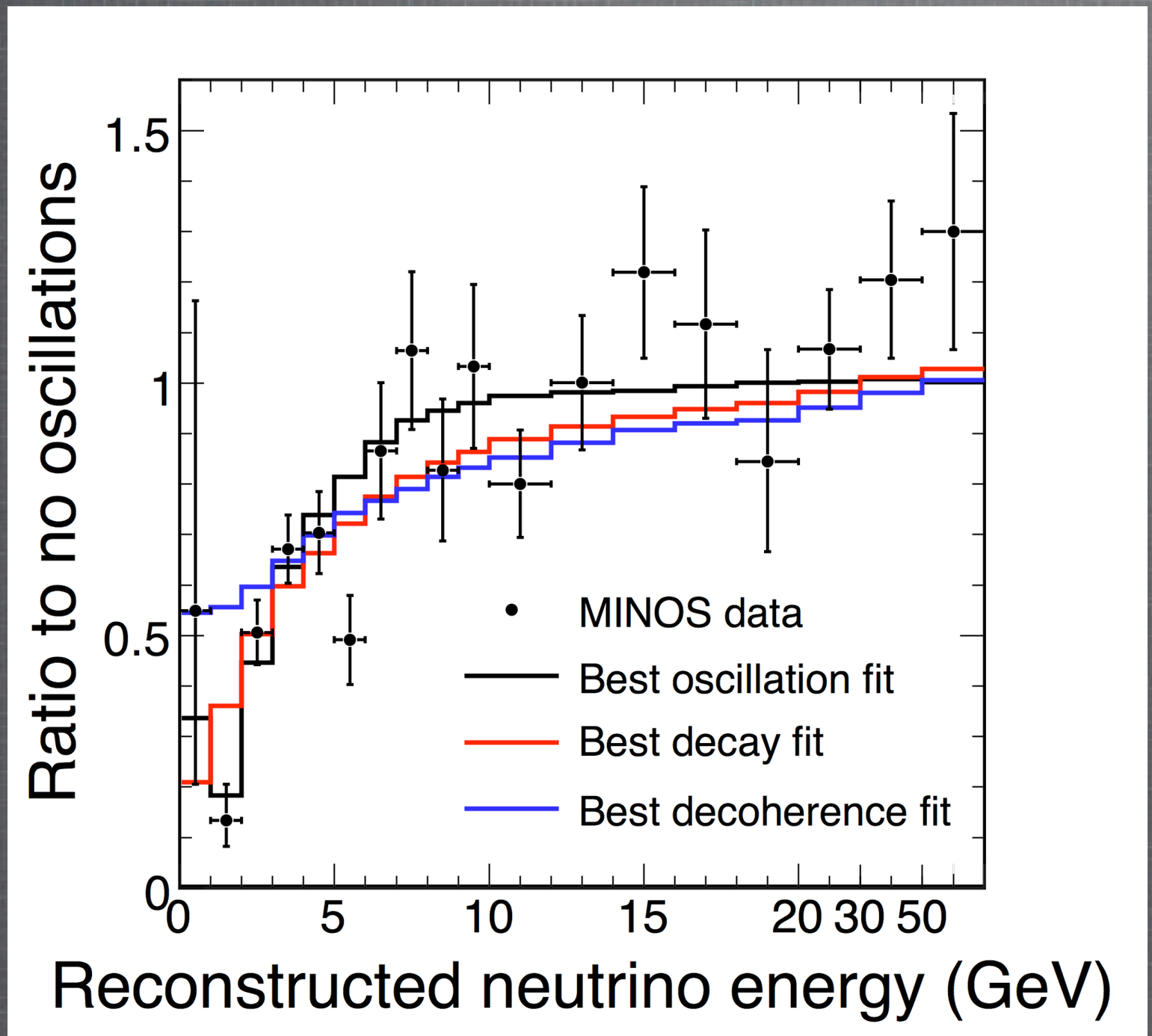
Contours



- **Constrained fit:**
  - $\Delta m^2 = (2.43 \pm 0.13) \times 10^{-3}$ eV^2 (68% CL)
  - $\sin^2(2\theta) > 0.90$ (90% CL)
  - χ^2/ndof = 90/97

- **Unconstrained fit:**
  - $\Delta m^2 = 2.33 \times 10^{-3}$ eV^2
  - $\sin^2(2\theta) = 1.07$
  - $\Delta\chi^2 = -0.6$

Alternative Hypotheses



Decay:

$P_{\mu\mu} = (\sin^2\theta + \cos^2\theta \exp(-\alpha L/E))^2$

χ^2/ndof = 104/97

$\Delta\chi^2 = 14$

Disfavored at 3.7 σ

Decoherence:

$P_{\mu\mu} = 1 - \frac{1}{2} \sin^2(2\theta) (1 - \exp(-\mu^2 L/2E))$

χ^2/ndof = 123/97

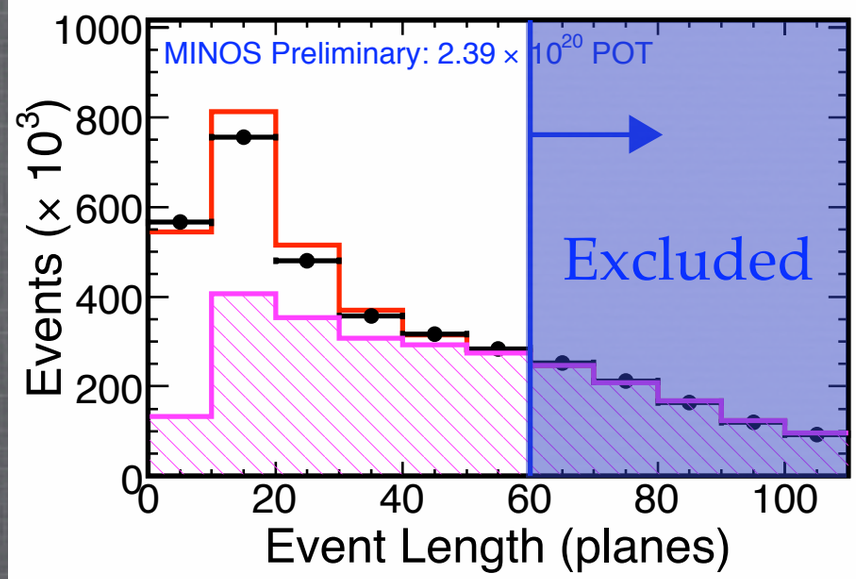
$\Delta\chi^2 = 33$

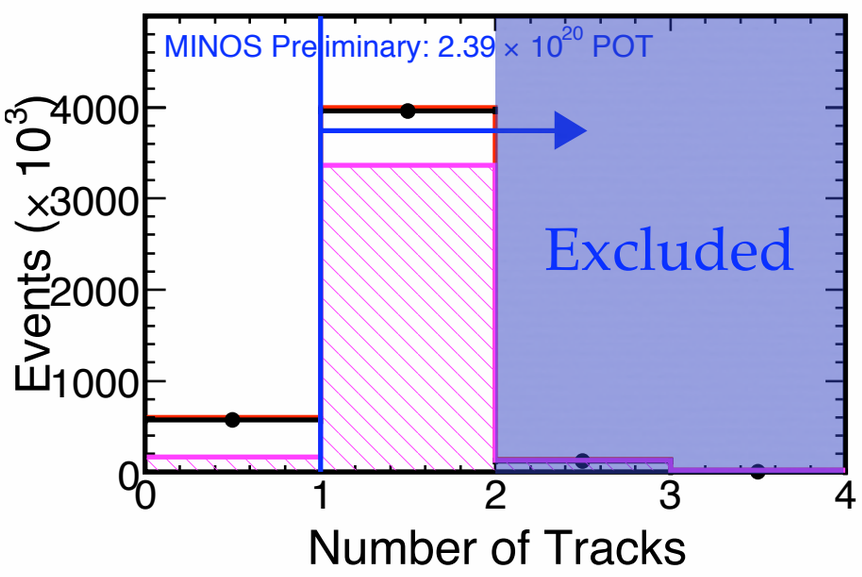
Disfavored at 5.7 σ

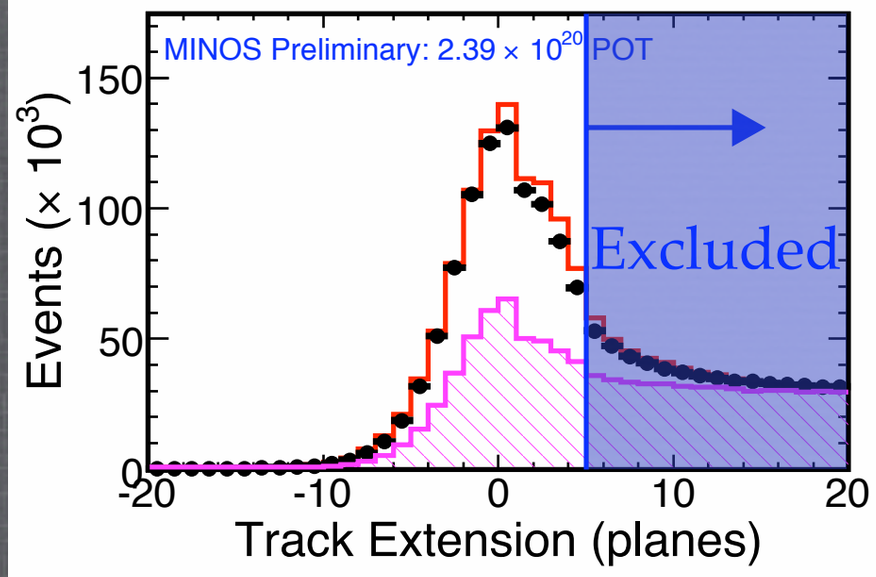
NC Analysis

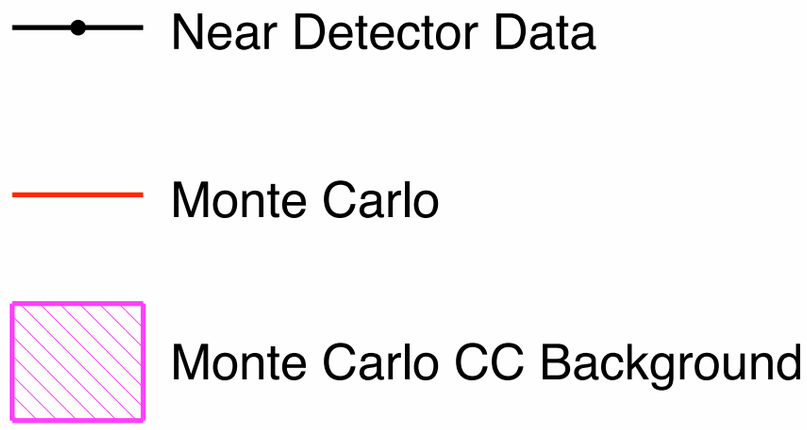
The search for sterile neutrinos

NC Event Selection in the ND



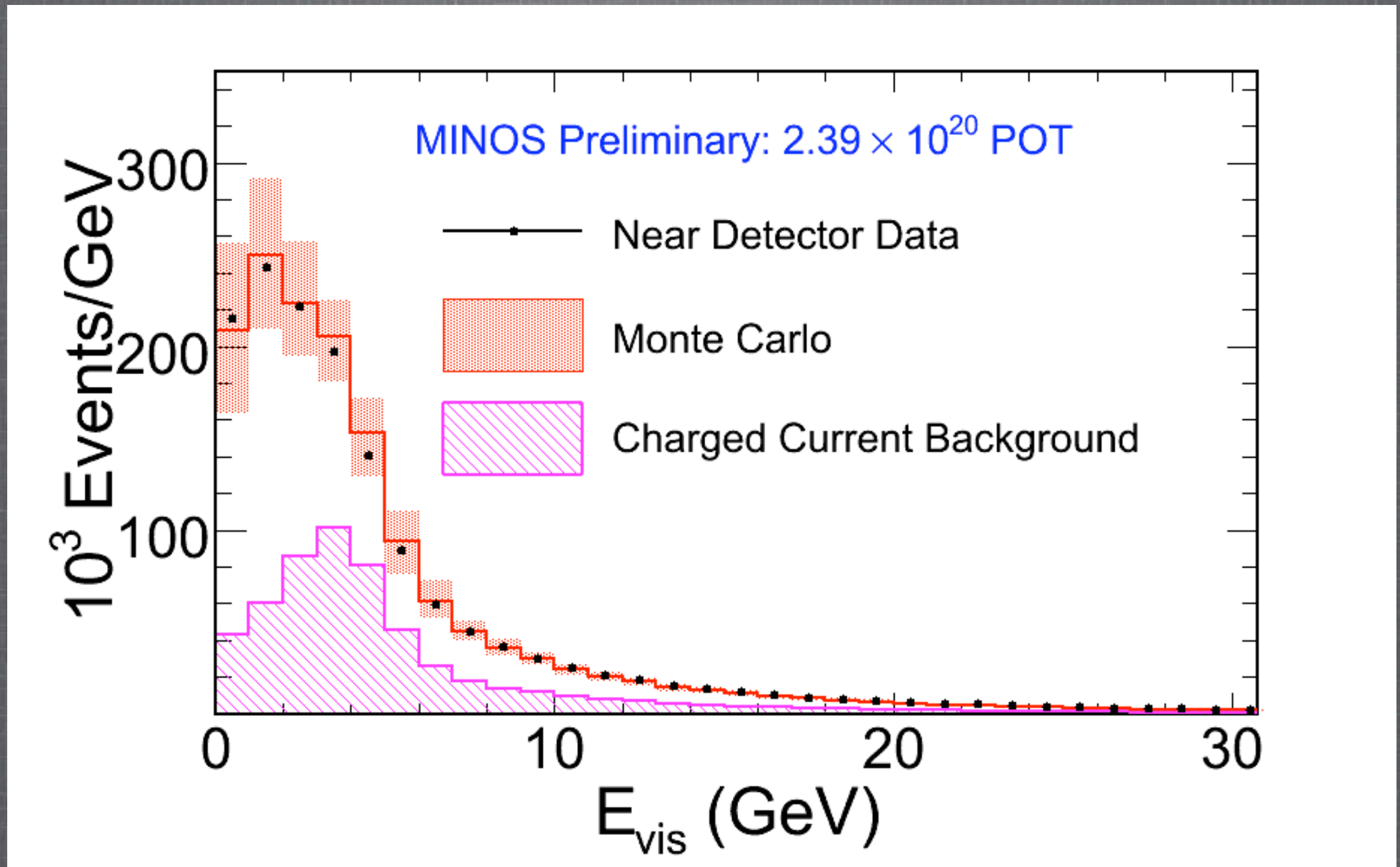






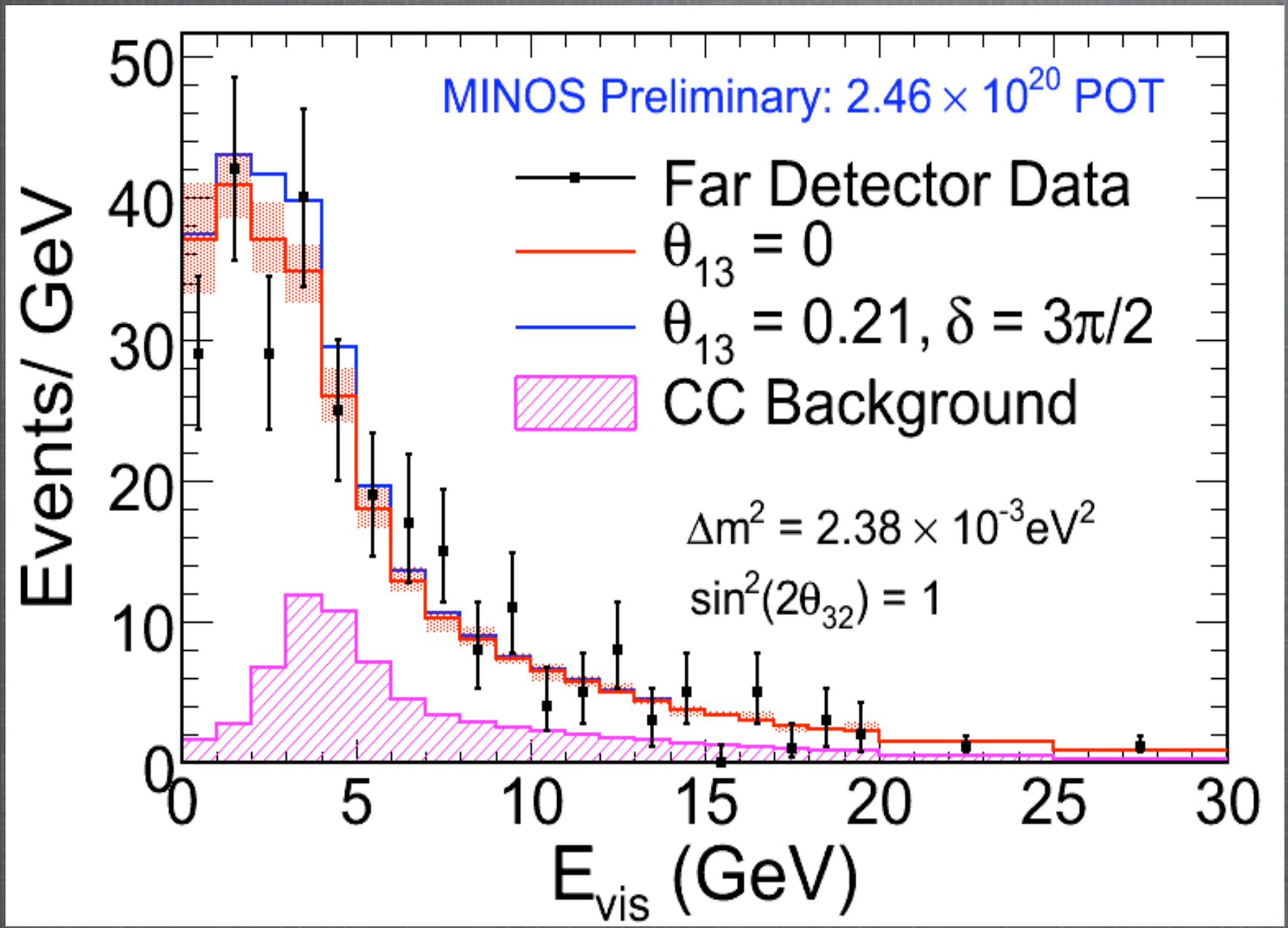
- Since NC events probe active flavors, a depletion of NC events in the FD can only be explained by ν_s.
- We select reconstructed "shower-like" (short) events that fall within a fiducial volume.

Measured Near Detector Spectrum



NC event selection efficiency is 90%, purity is 60%.

3-Flavor Analysis Results



Data / MC Comparison for $\theta_{13} = 0$

Energy Range (GeV)	0 - 3	0 - 120
Data	100	291
MC	115.16 ± 7.67	292.63 ± 15.02
Significance (σ)	1.15	0.10

- For $E_{vis} < 3$ GeV, $f_{NC} < 35\%$ at 90% CL.
- For $E_{vis} < 120$ GeV, $f_{NC} < 17\%$ at 90% CL.

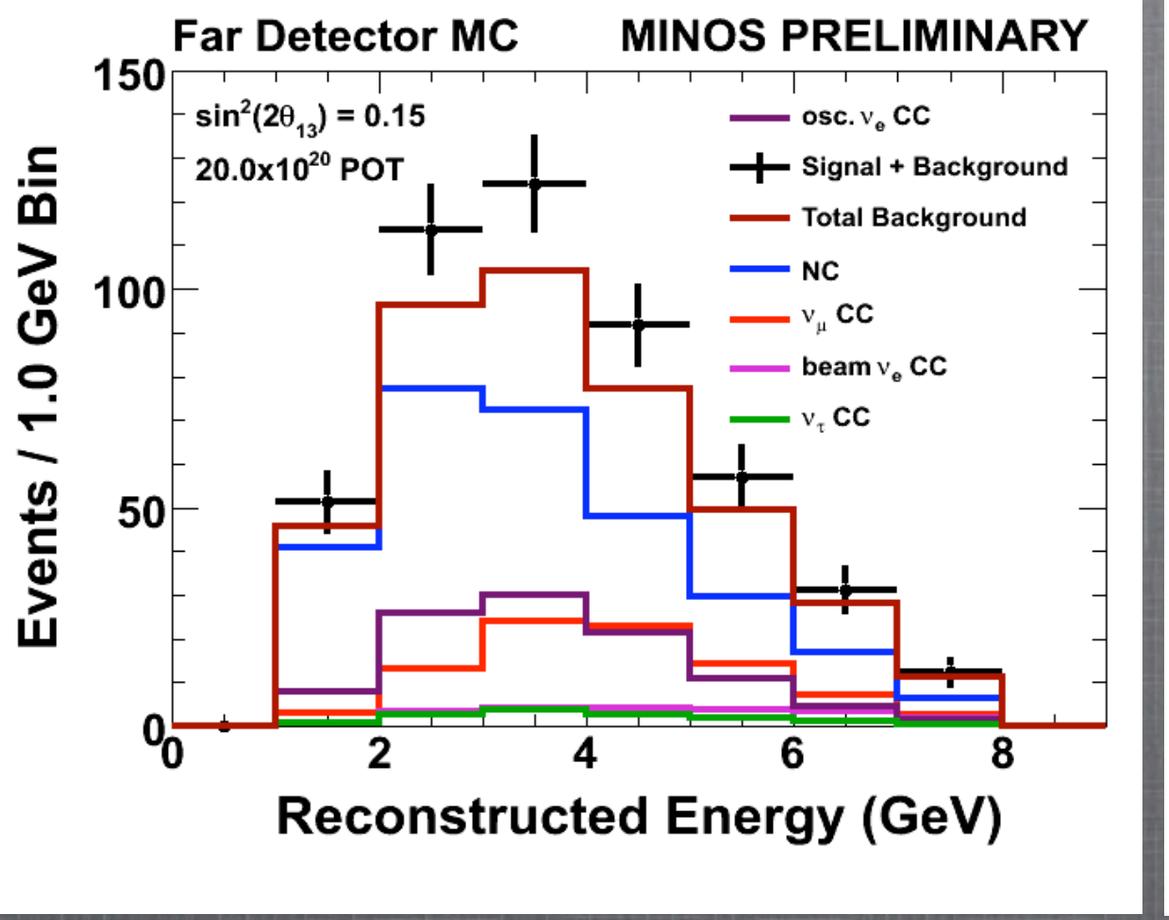
Other Finalized Analyses

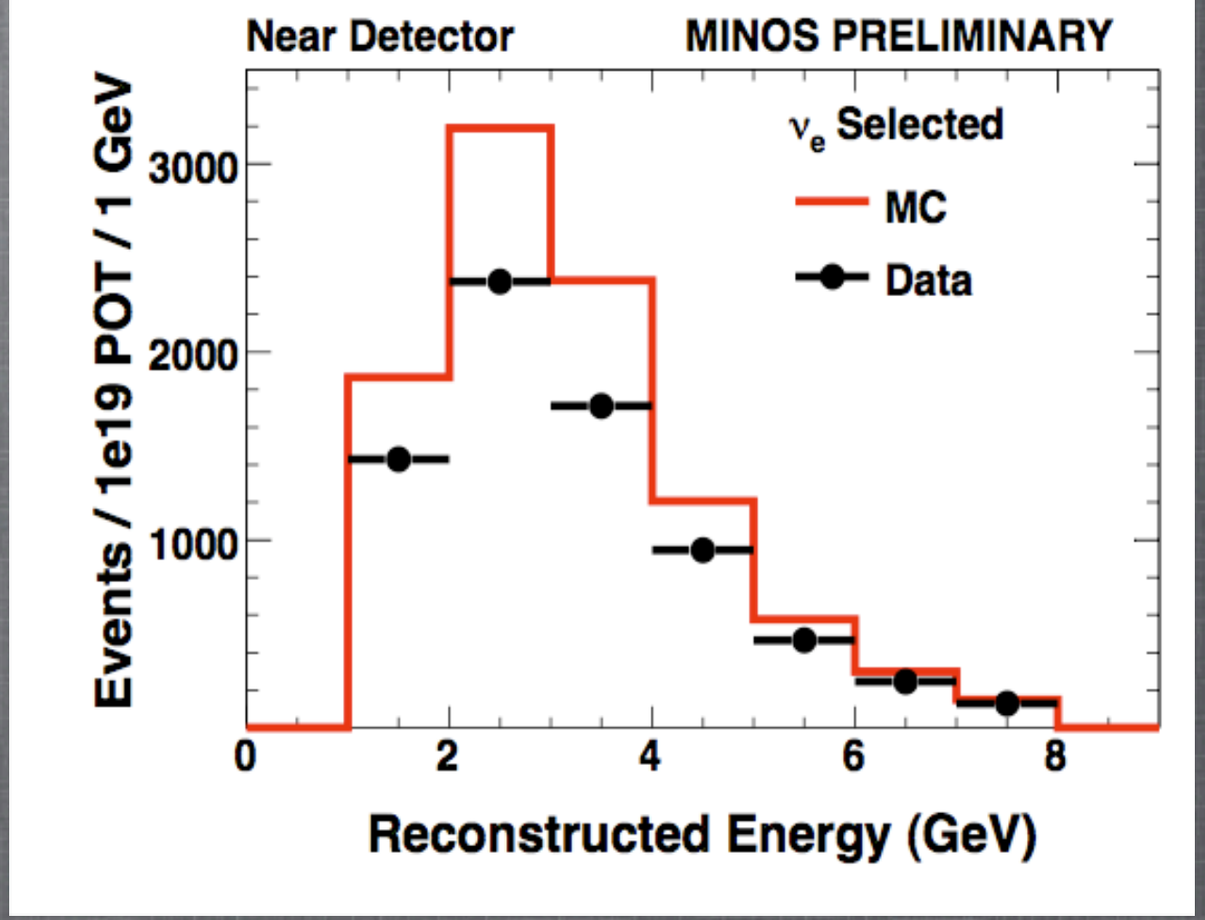
- **"Sudden stratospheric warmings seen in MINOS deep underground muon data"**: High-energy cosmic muon rate is strongly correlated to temperature changes in the upper atmosphere. MINOS has shown that (under)ground-based high statistics cosmic muon measurements are a new tool to be used in tracking meteorological phenomena in the upper atmosphere.
- "**Testing Lorentz Invariance and CPT Conservation with MINOS Near Detector Neutrinos**": search for a sidereal signal in the MINOS ND. Upper limits set on individual SME Lorentz and CPT violating terms.
- "**Observation of deficit in NuMI neutrino-induced rock and non-fiducial muons in MINOS far detector and measurement of neutrino oscillation parameters**": see poster by Aaron McGowan

ν_e CC Analysis

The search for ν_e appearance

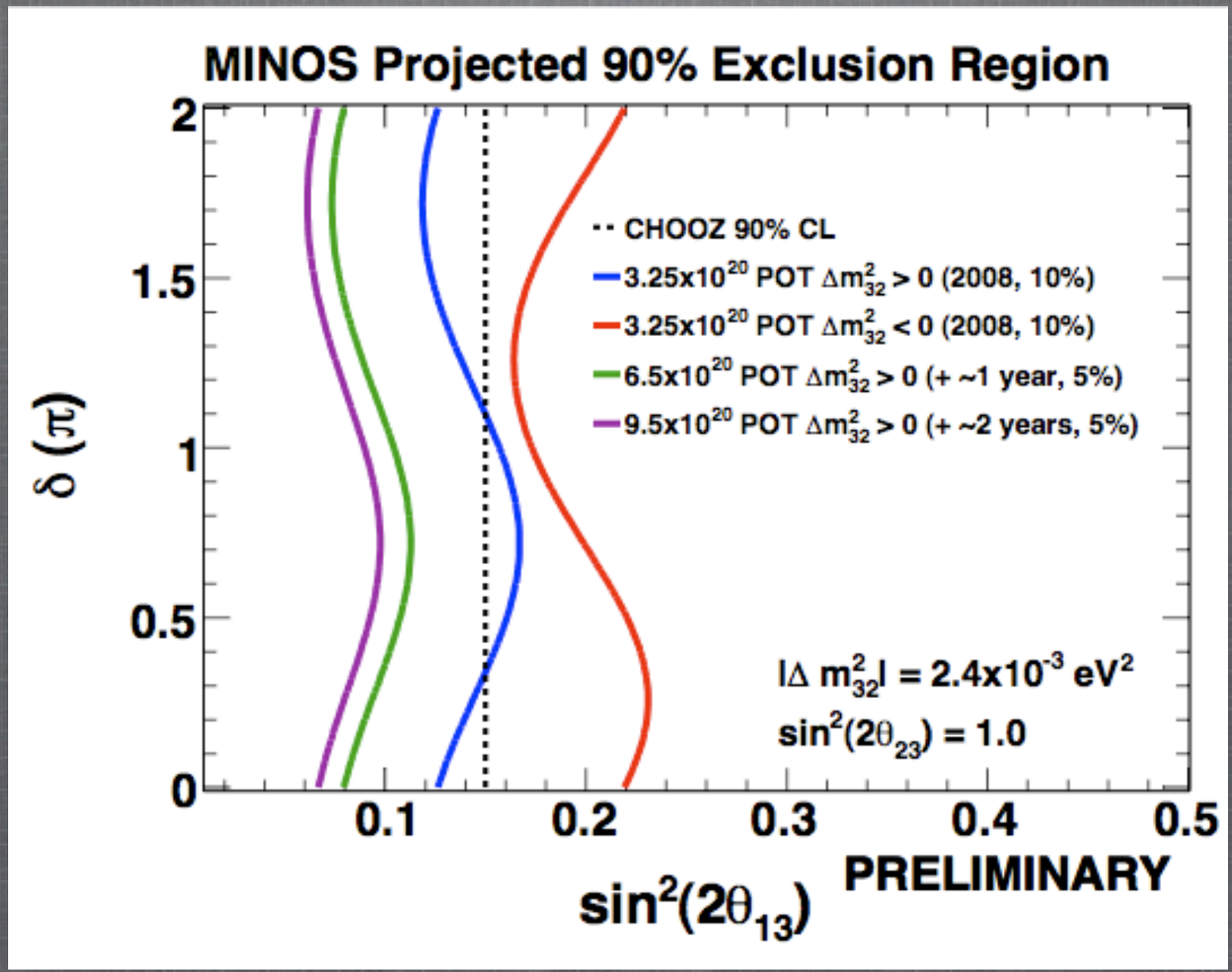
ν_e Background Estimates





- Measurement dominated by backgrounds: at the CHOOZ limit, 12 ν_e events are expected with 42 background events (for 3.25 x 10^{20} POT).
- Dominant background is NC events, with other significant contributions coming from ν_μ CC events and intrinsic beam ν_e events.
- We see a very large discrepancy between selected ν_e ND MC and data events.
- Two new data-driven methods have been developed to resolve the MC/data difference - see posters by Steven Cavanaugh and Lisa Whitehead for details.

ν_e Sensitivity



- Projected limits for expected MINOS integrated exposures for the next few years.
- Inverted hierarchy (in red) shown only for lowest exposure.
- MINOS can improve upon the CHOOZ limit by ~x2.

Other Analyses in the Works

- Anti-neutrino oscillation measurements
- ND measurements:
  - Inclusive CC cross-section and structure functions
  - M_A extraction from quasi-elastic events
  - NC coherent scattering on Fe
  - Cosmic ray studies

Conclusions

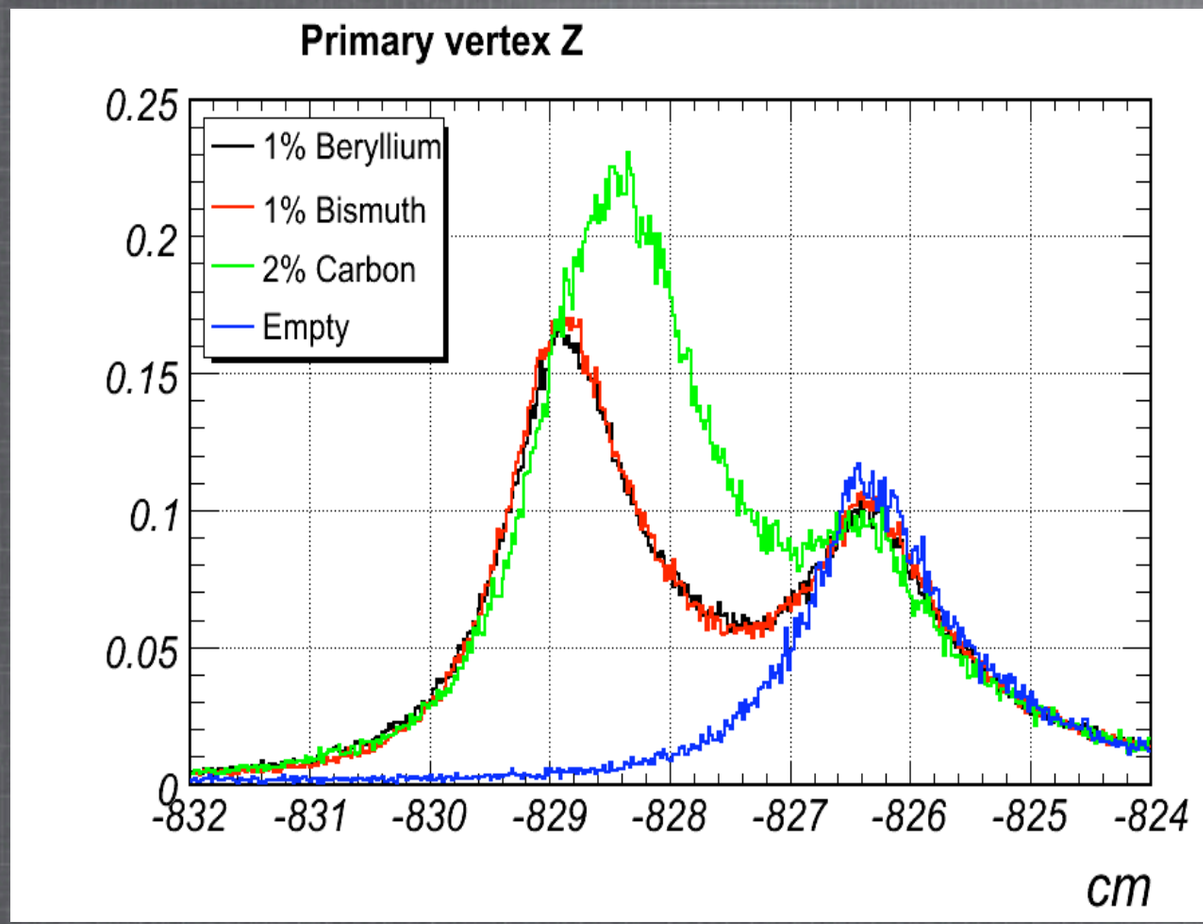
- 2007-08 has been a very productive year for MINOS!
- Latest ν_μ CC analysis results (3.36 x 10^{20} POT):
  - $\Delta m^2 = (2.43 \pm 0.13) \times 10^{-3}$ eV^2 (68% CL),
  - $\sin^2(2\theta) > 0.90$ (90% CL),
  - Decay and decoherence models disfavored at 3.7 and 5.7 σ respectively.
- NC analysis results (2.46 x 10^{20} POT): fraction of disappearing NC events < 0.17 at 90% CL.
- Great progress in understanding the backgrounds and systematics in the νe appearance measurement; first results are expected later this year.
- Results from MIPP expected later this year, expected uncertainty on ν flux is ~15%.
- Many ND ν interaction measurements also expected later this year.
- Thanks to FNAL AD, CD, and administration for all their hard work and support!

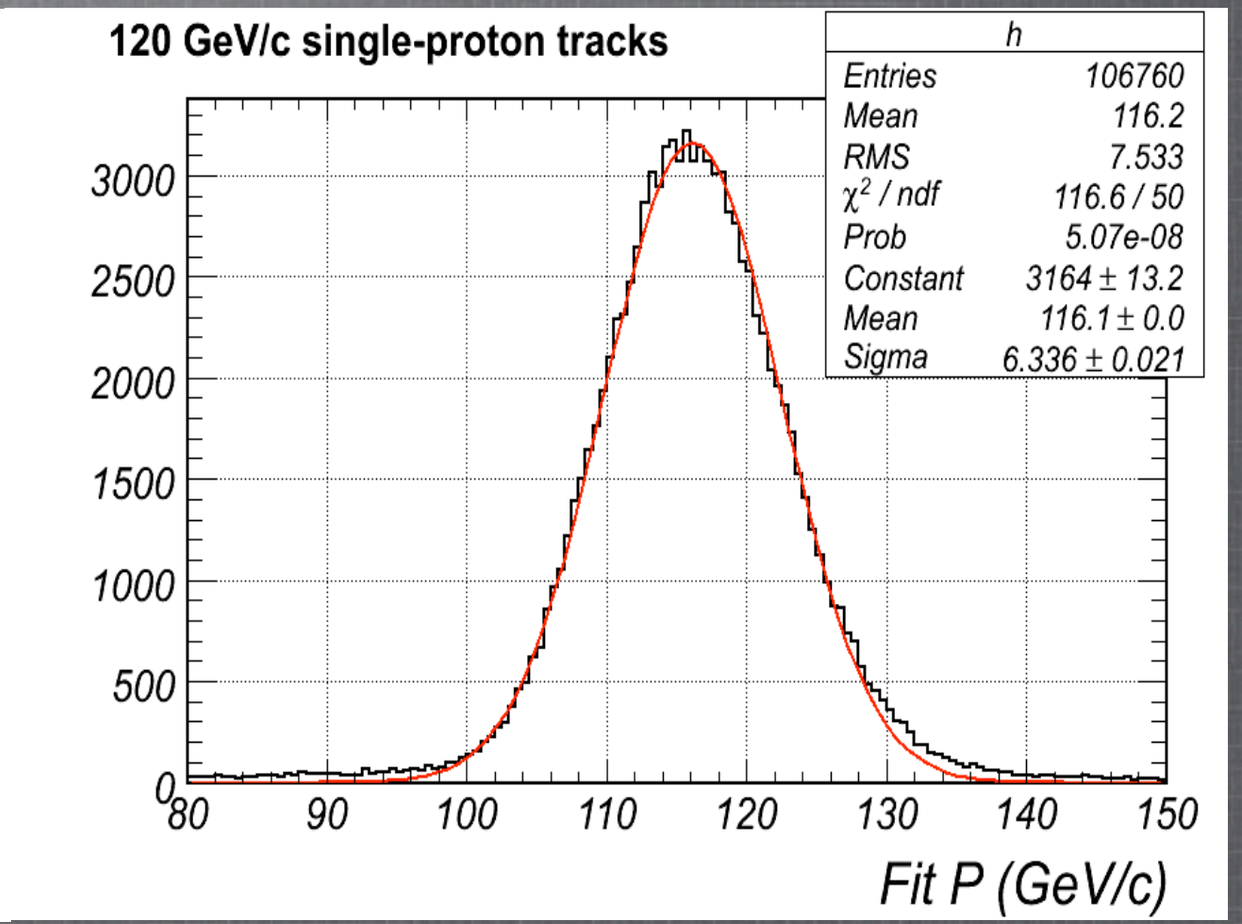
Backup Slides

Outline of the Rest of this Talk

- The MINOS Experiment
- What's new (2007-08)
- Future Prospects

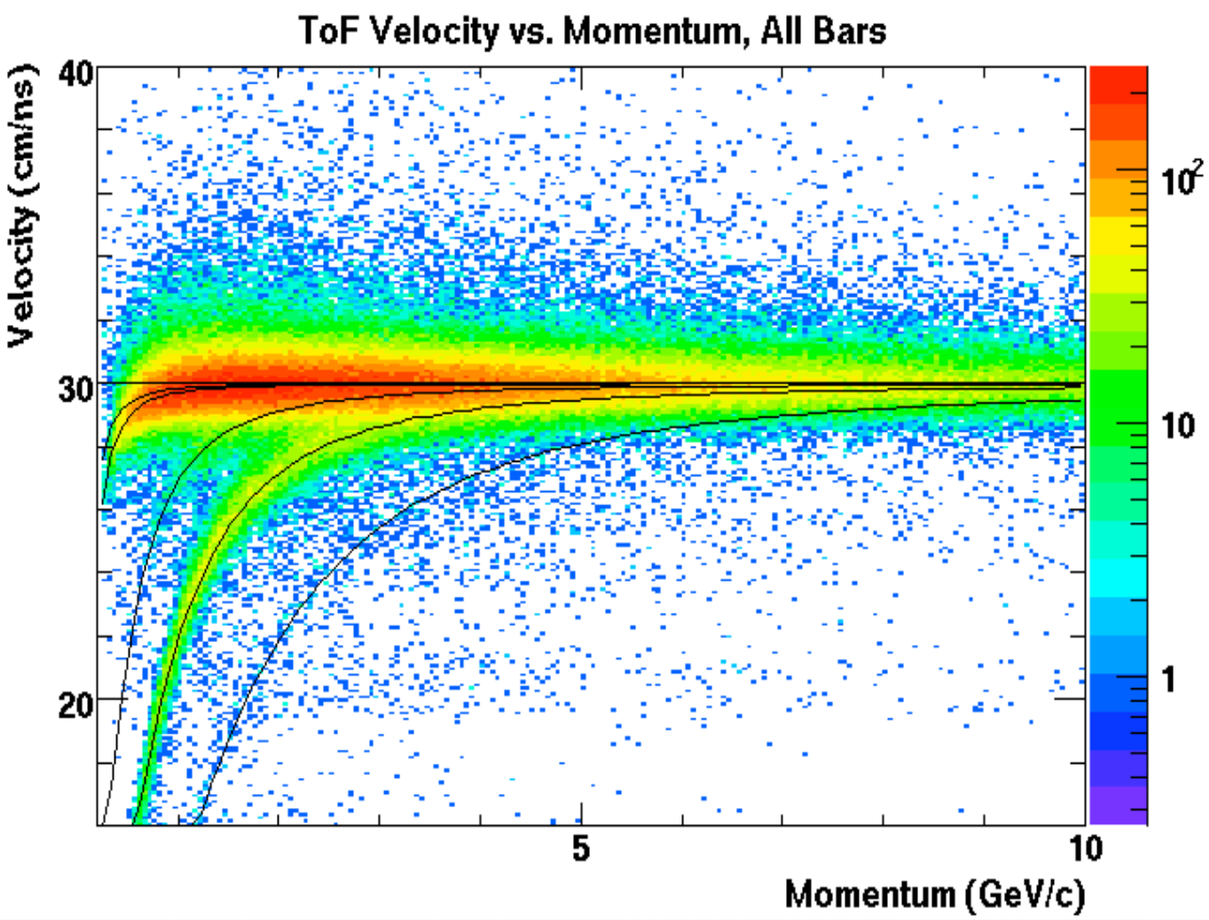
MIPP Performance

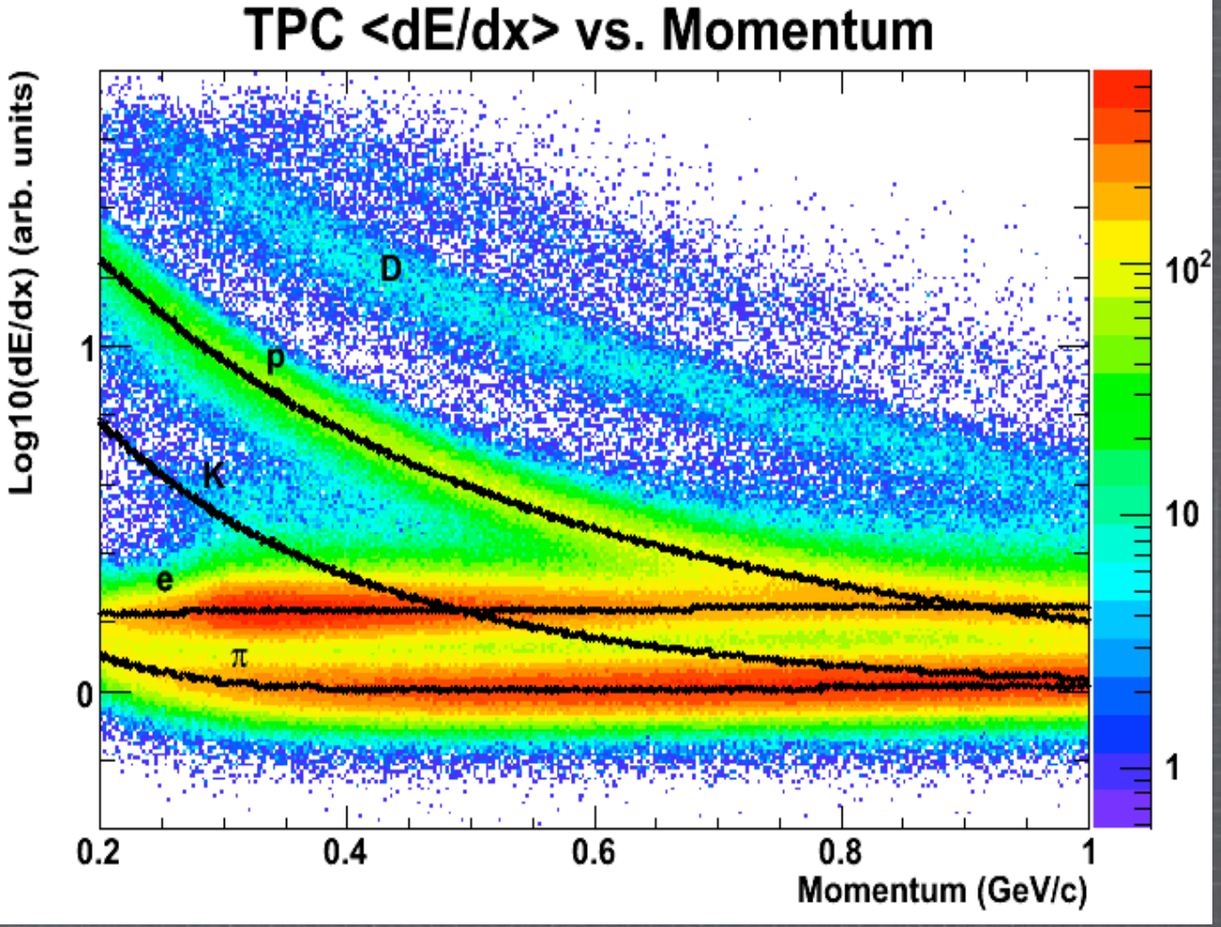




- Momentum resolution is ~5% at 120 GeV/c, much better at lower momenta.
- Vertex resolution is ~8 mm in the beam direction, ~2 mm transverse.
- Reconstructed momentum appears to be systematically low by ~2%.

MIPP Performance

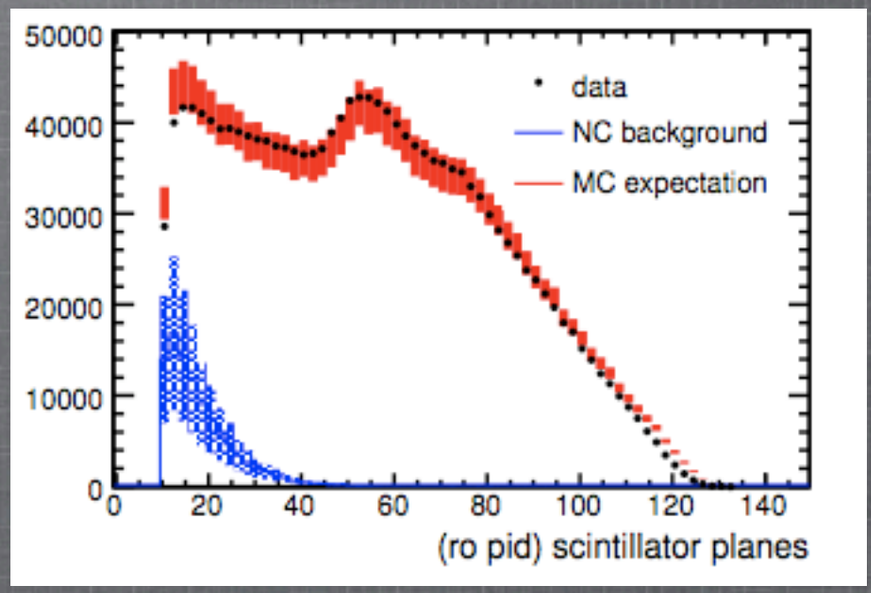


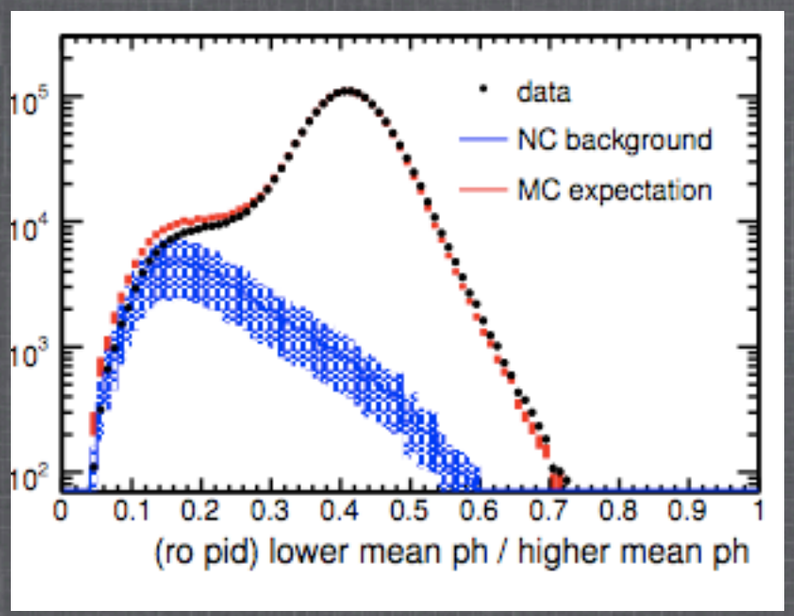


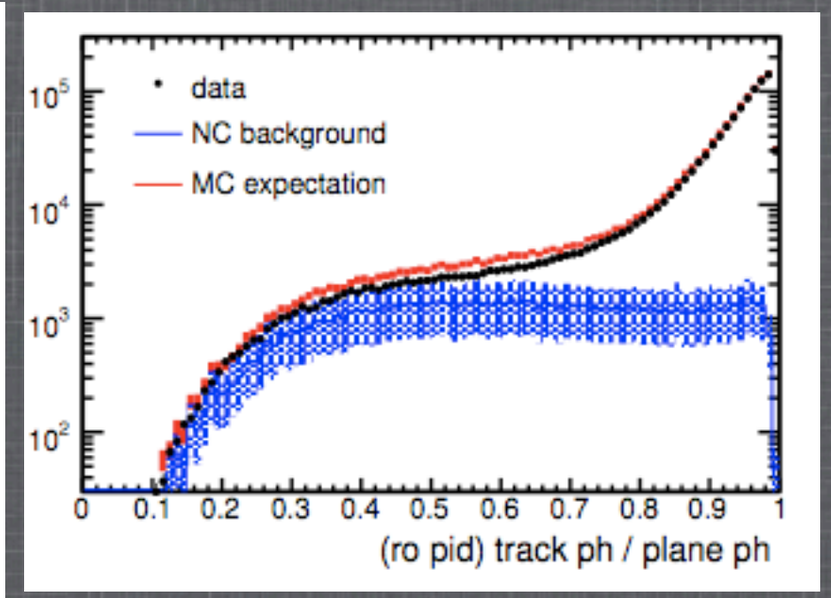
- Ckov has ~5 pe per β=1 particle.
- ToF resolution is ~300 ps
- TPC <dE/dx> resolution is ~12 %.

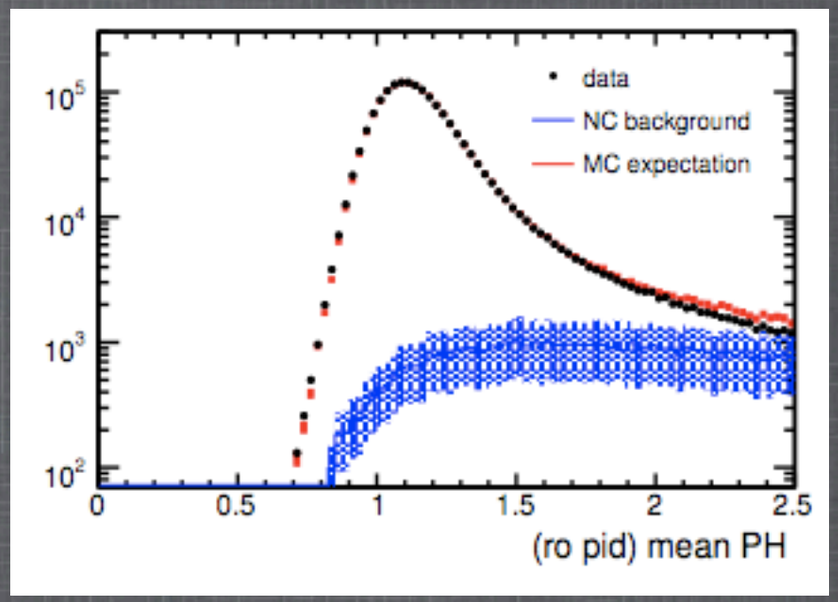
ν_μ CC/NC Separation

- CC/NC separation achieved via a kNN event selection based on:
  - Track length
  - Mean pulse height
  - Fluctuation in pulse height
  - Transverse track profile

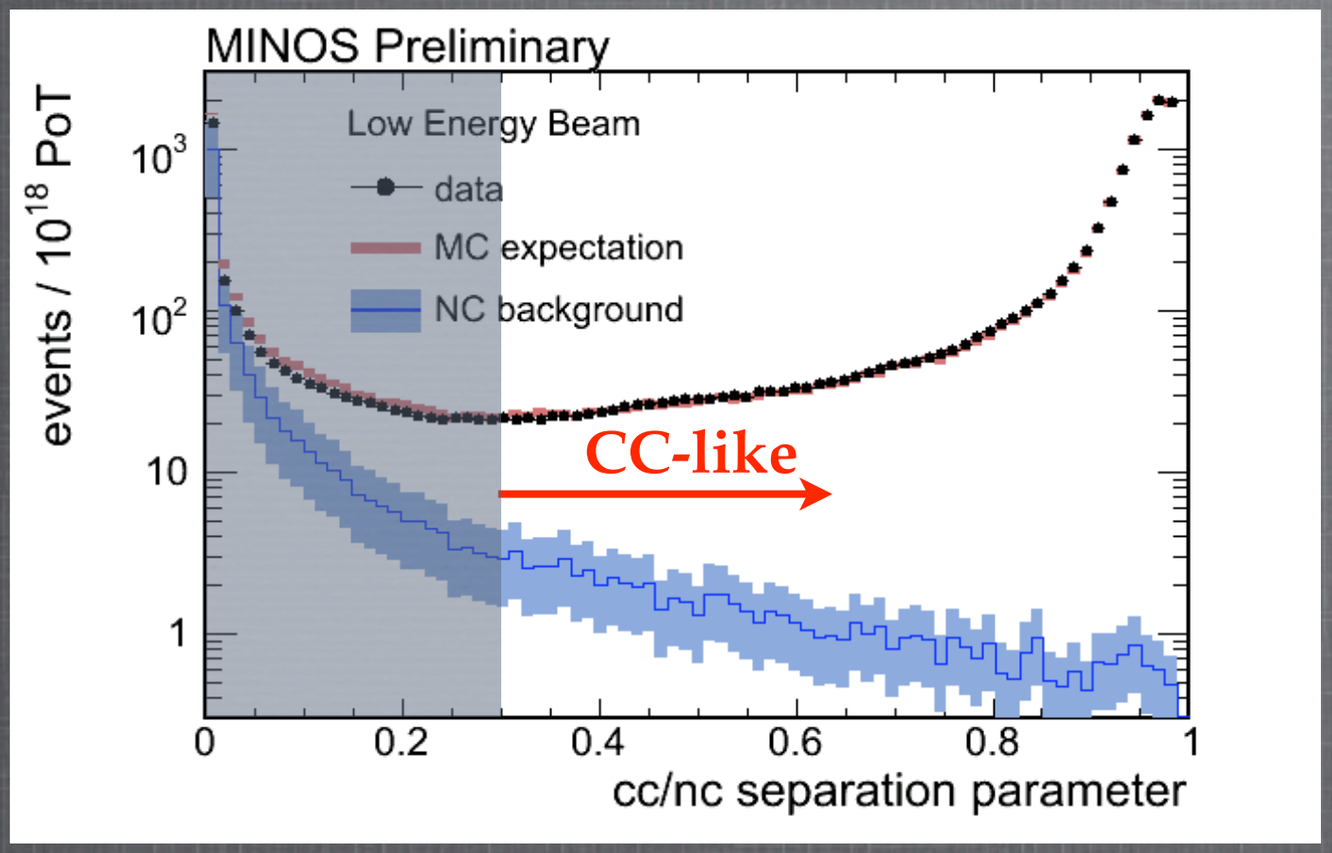


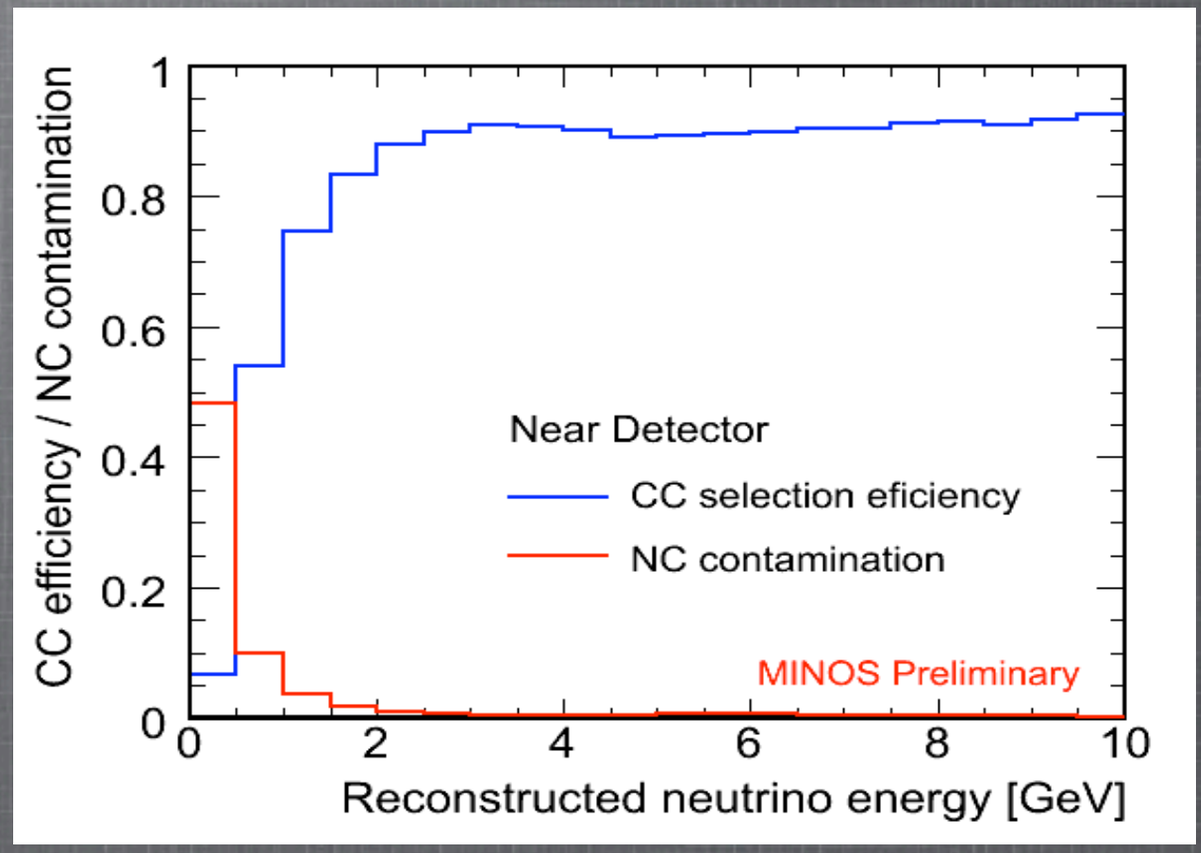






ν_μ CC Event Selection

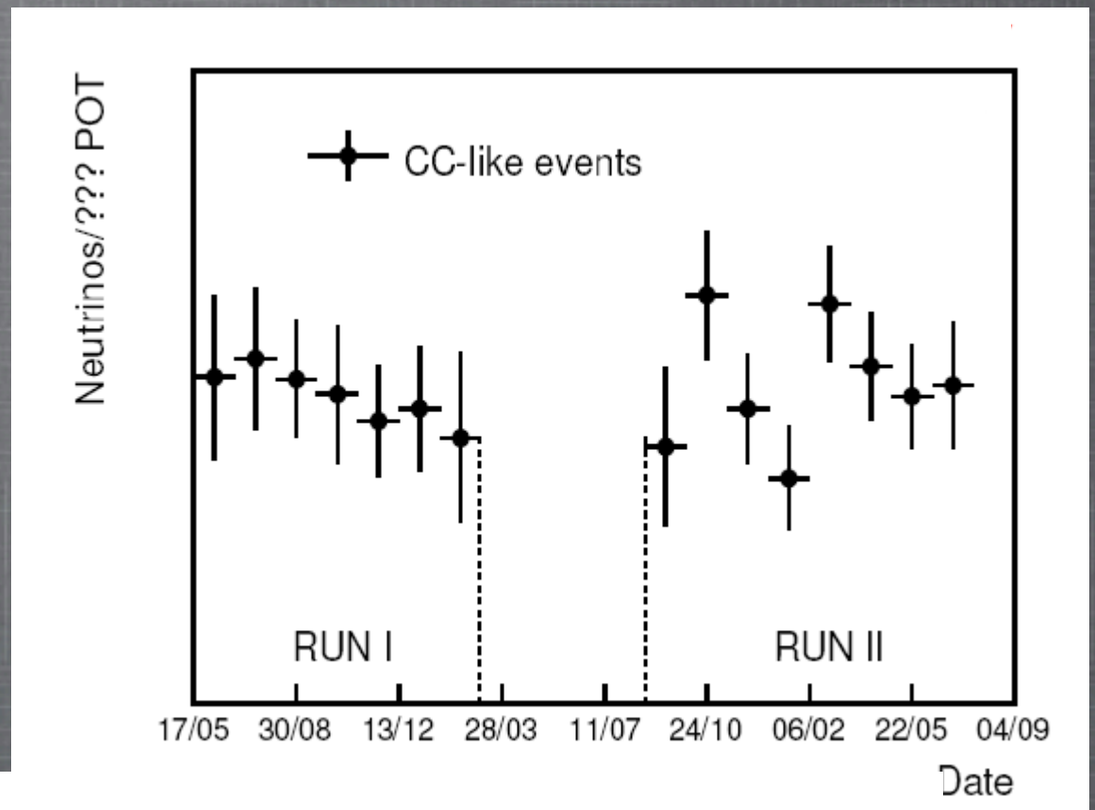


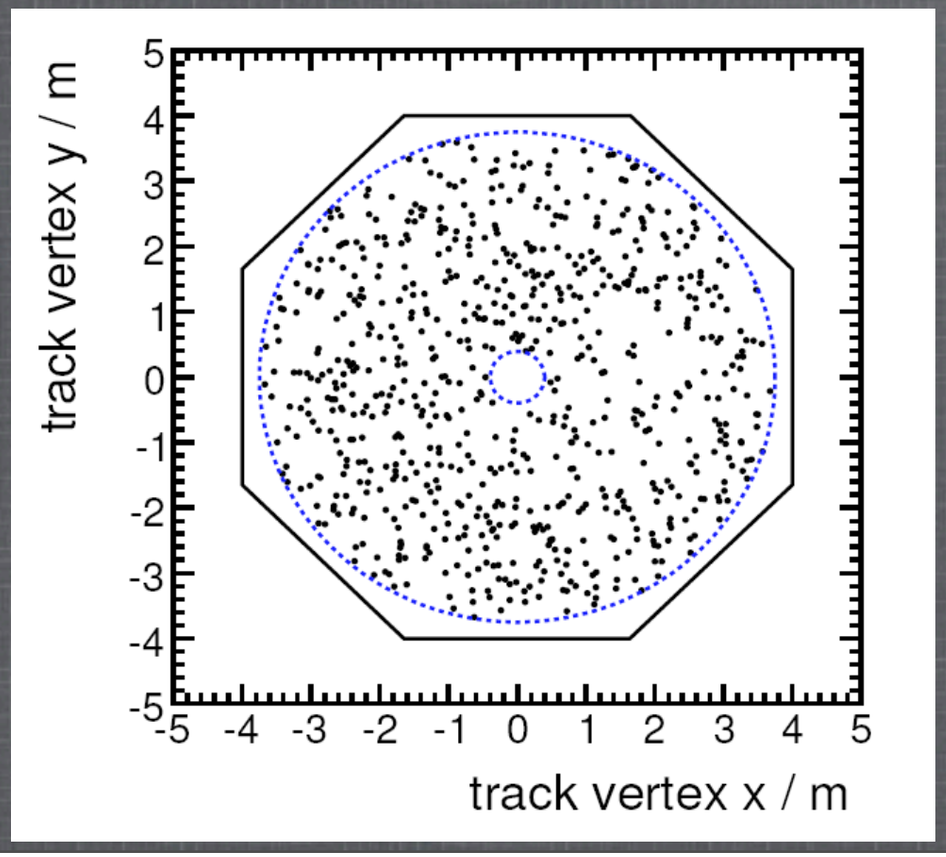


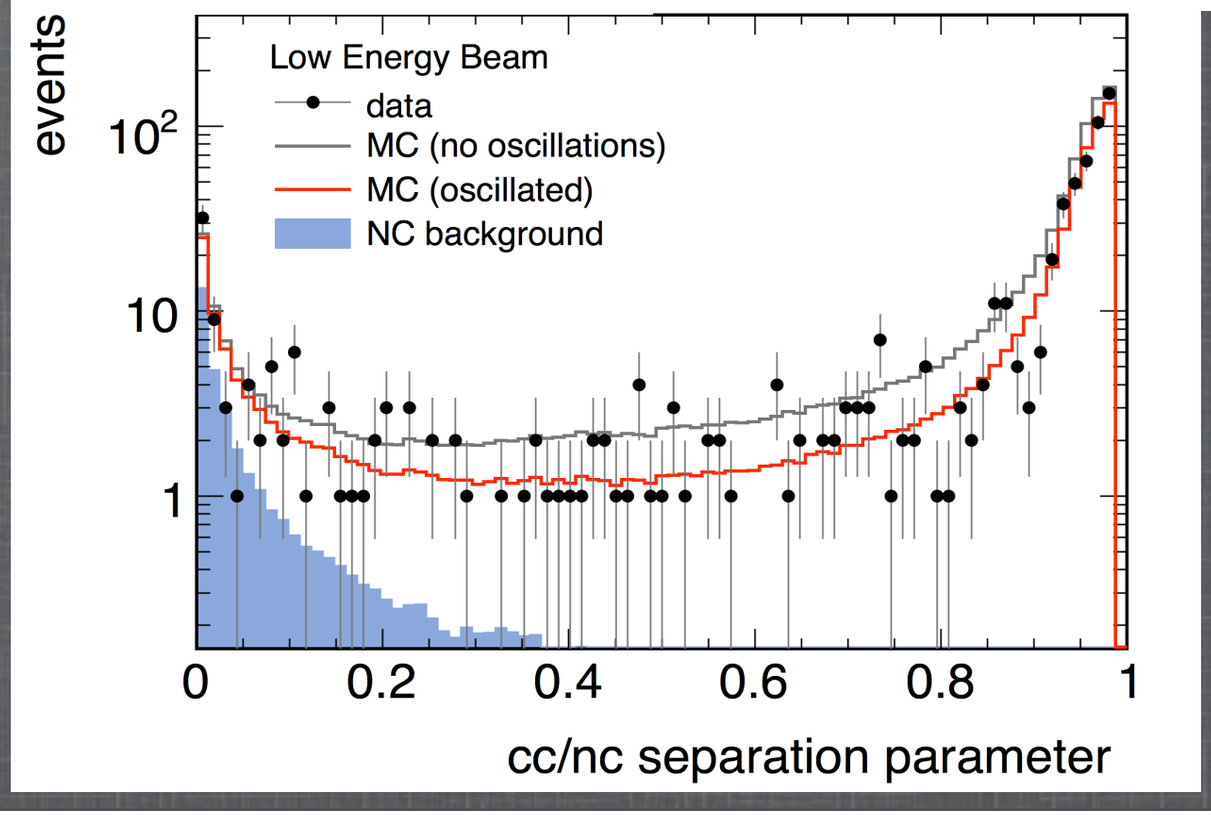
- Cut on separation parameter maximizes CC selection efficiency and minimizes NC background.
- Good agreement between data and MC above the CC/NC separation parameter cut.

Far Detector Low-level Data Quality Checks

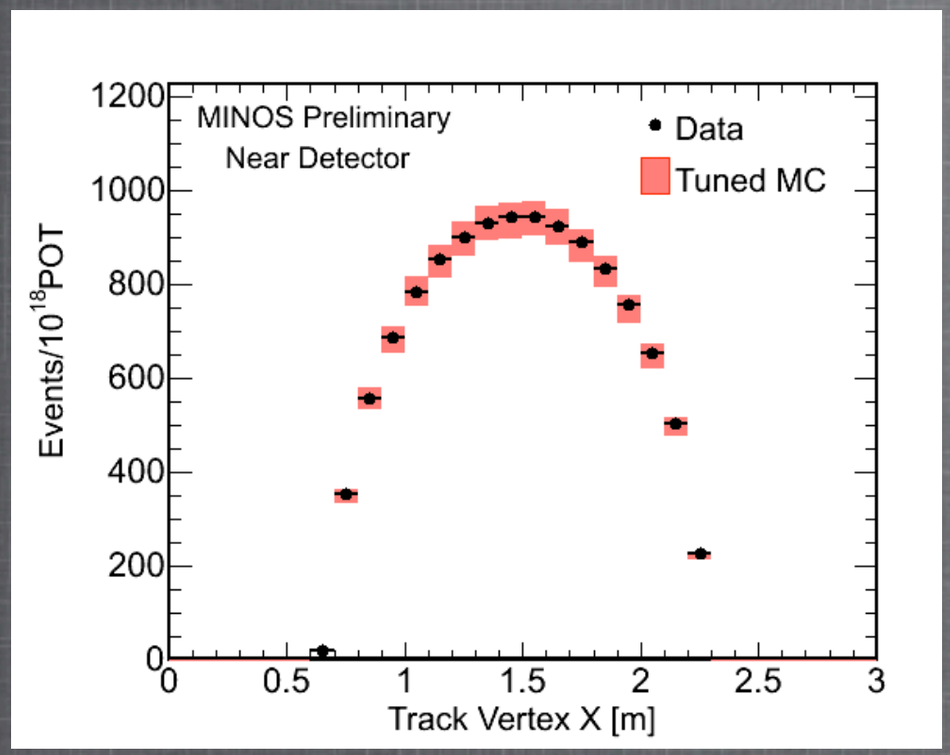
- FD energy spectrum is only looked at after performing:
  - low-level data quality checks
  - procedural checks

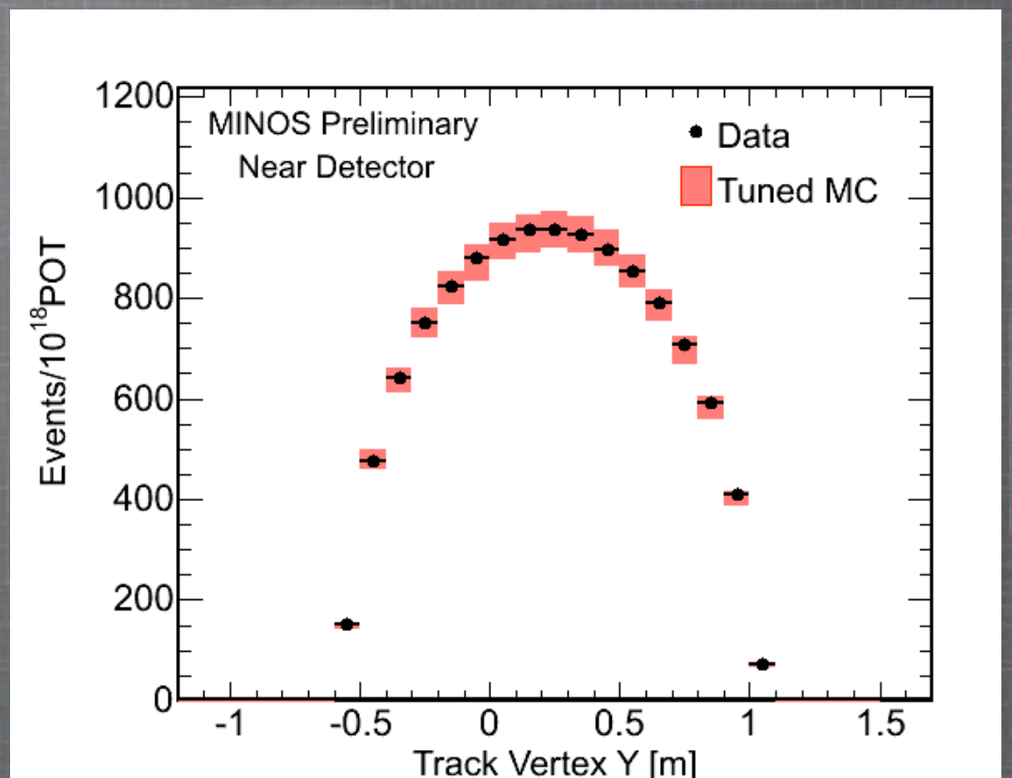


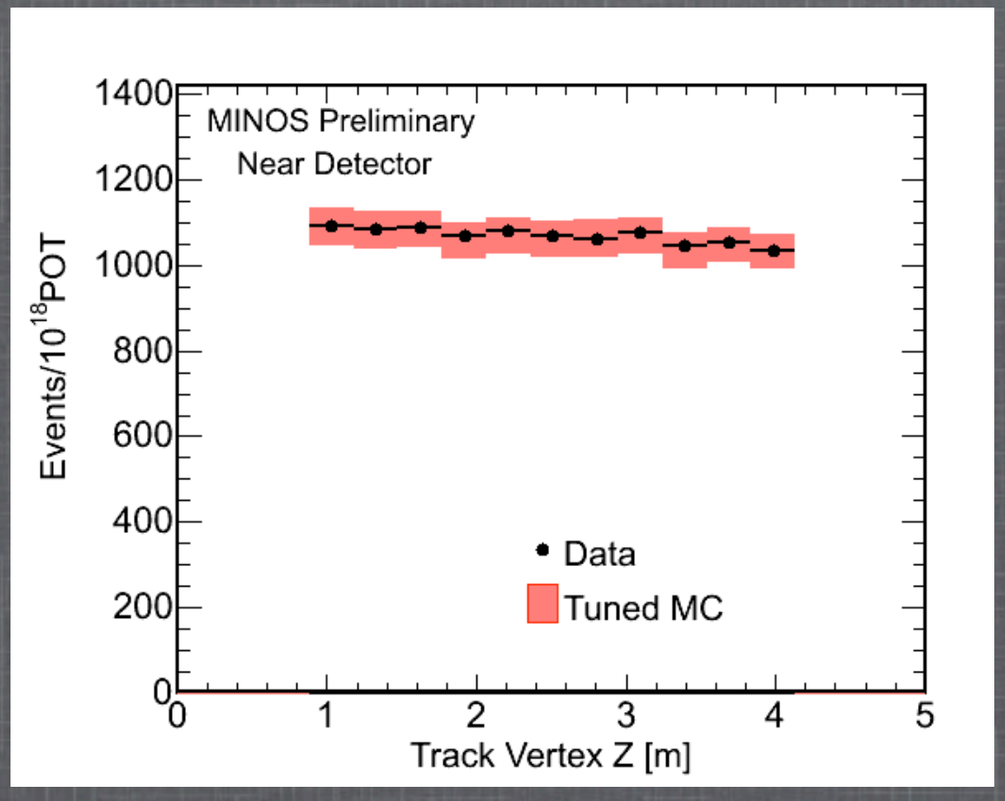




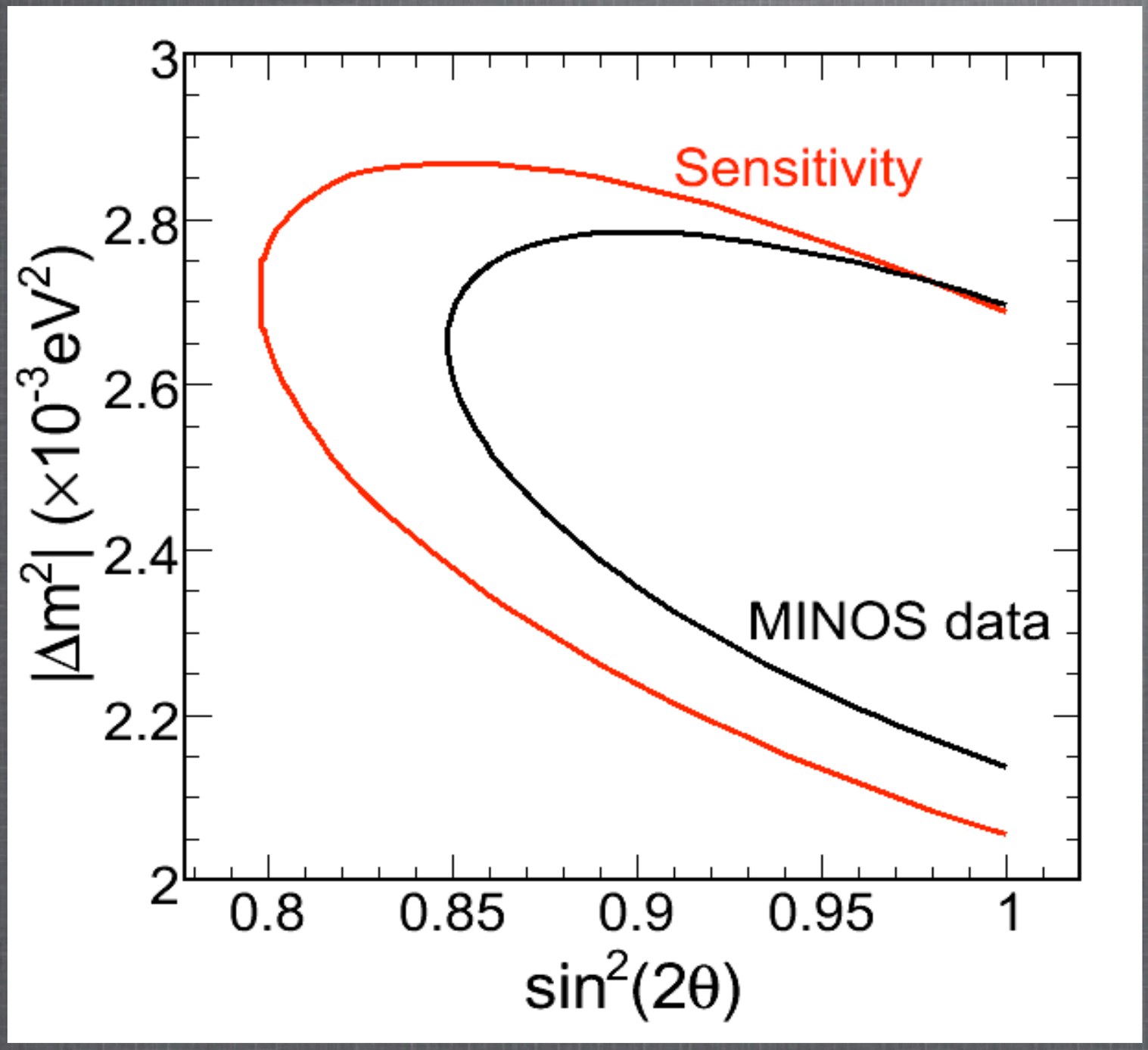
ND Distributions After Making PID Cut





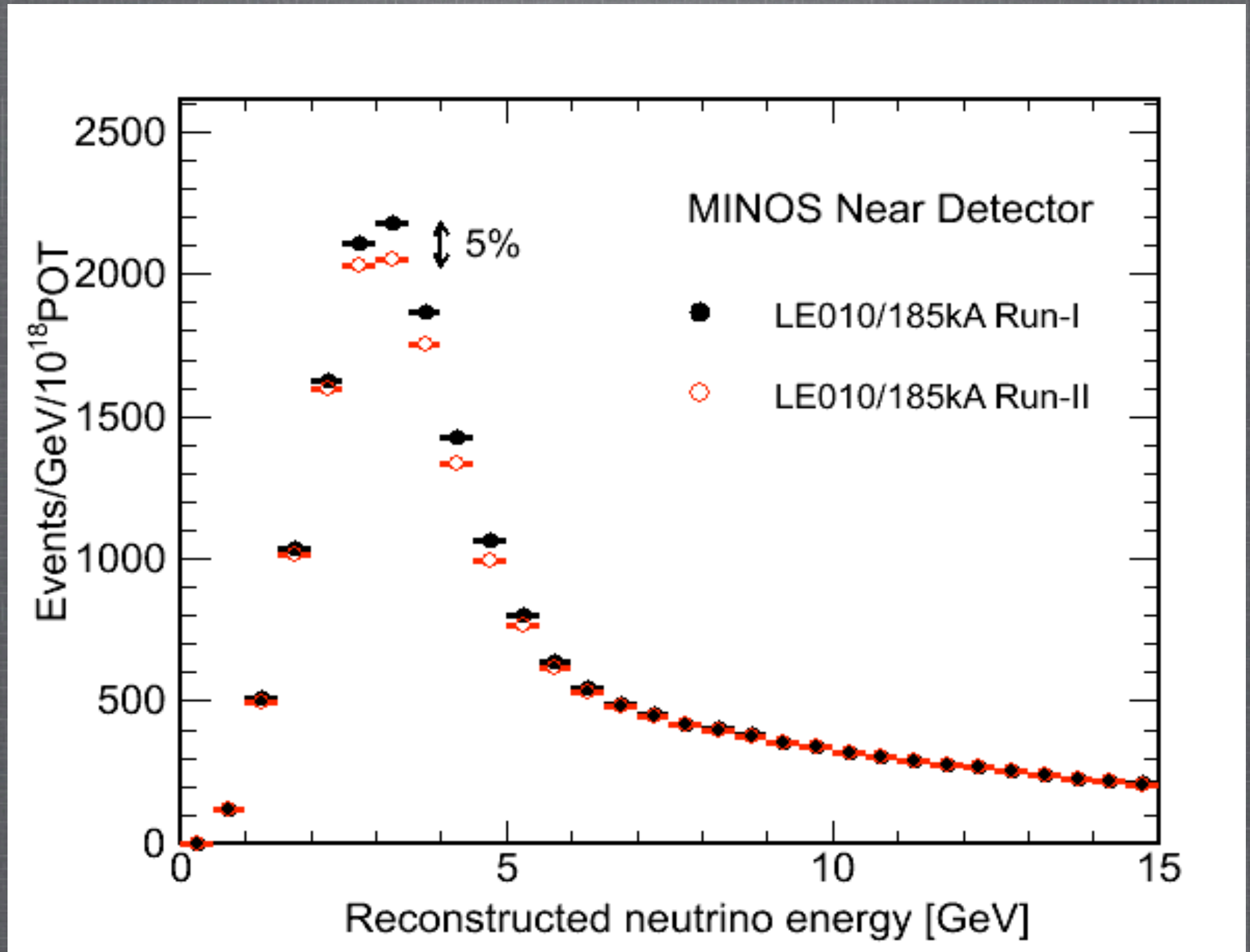


Sensitivity



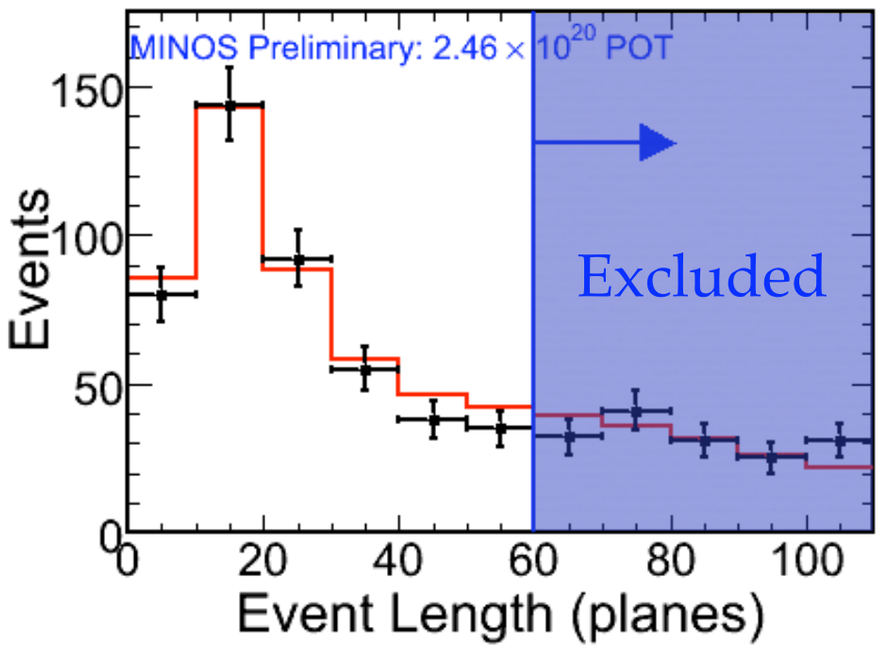
- Final contour is a bit smaller than the predicted sensitivity because $\sin^2(2\theta)$ falls in the unphysical region.
- A study shows that 26.5% of unconstrained fits have a fit value of $\sin^2(2\theta) \geq 1.07$
- Feldman-Cousins study indicates that our contours are slightly conservative.

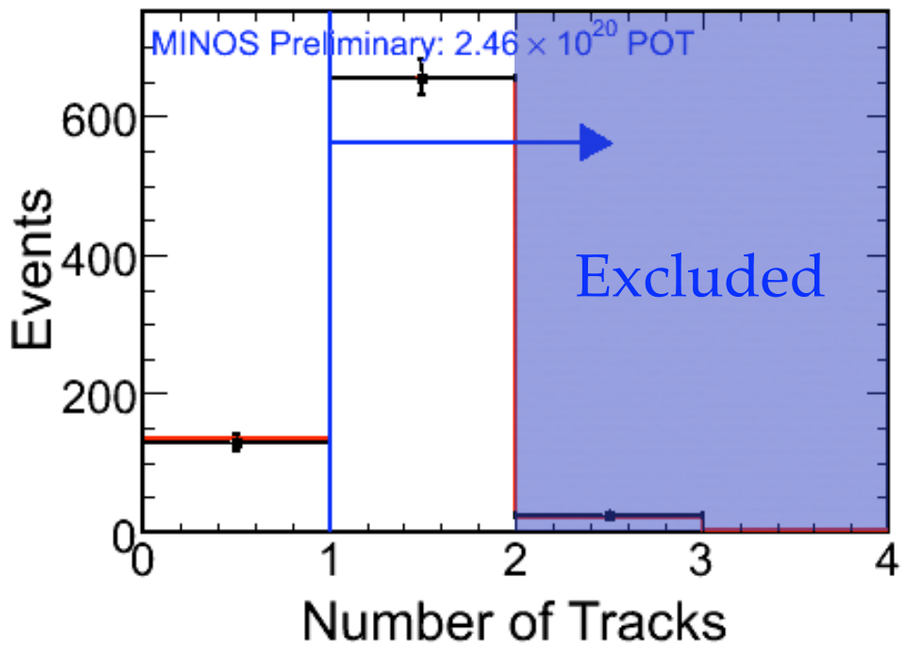
LE1 vs. LE2 Beam Configurations

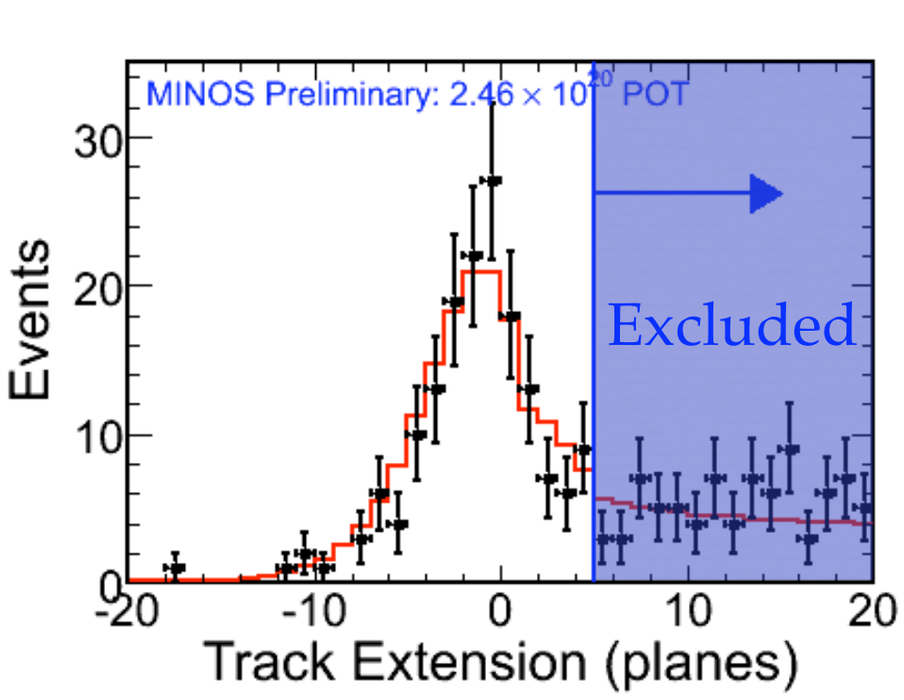


NC Event Selection in the FD

- Identical cuts are made in FD as in ND.
- MC oscillated with 2007 MINOS CC best fit values of $\Delta m^2 = 2.38 \times 10^{-3}$ eV^2 and $\sin^2(2\theta) = 1$.





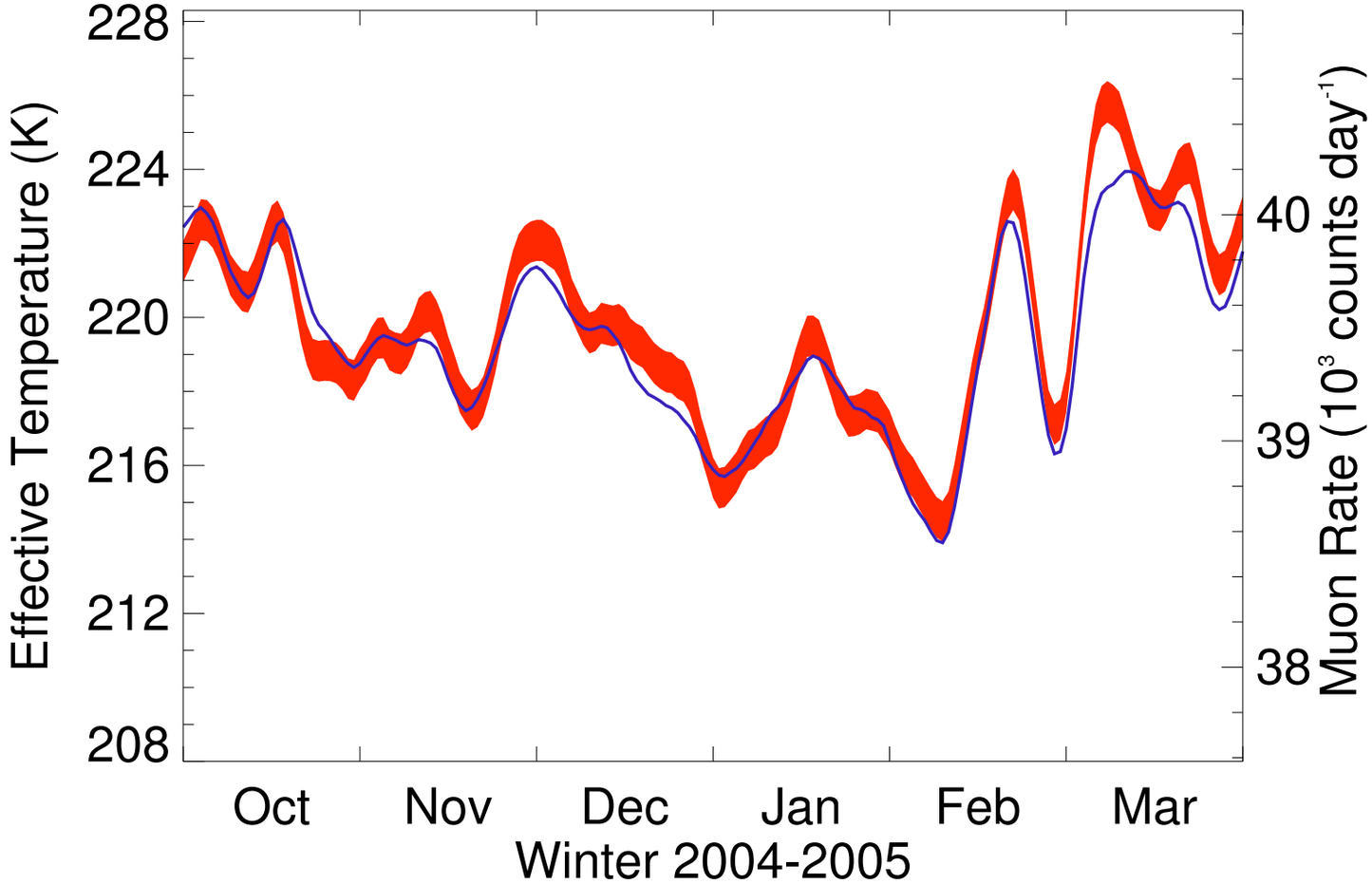


Far Detector Data

Monte Carlo

Cosmic Rays and Upper Atmospheric Weather

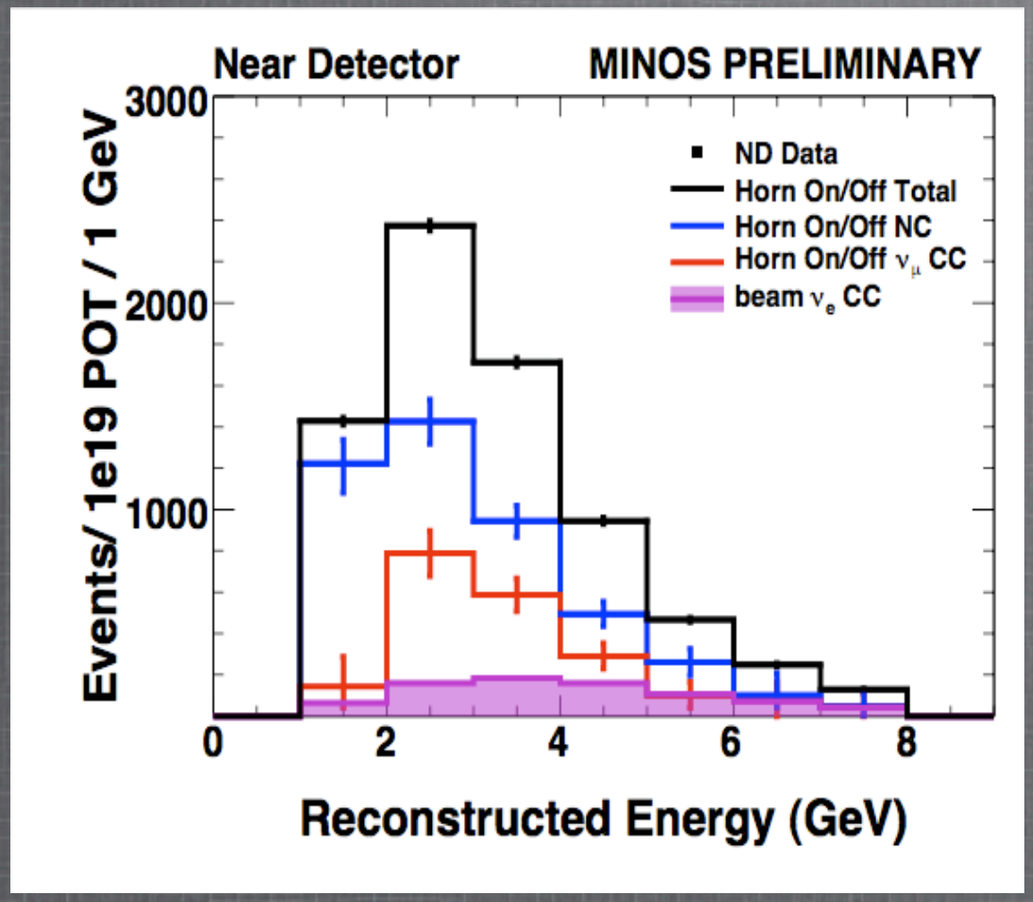
Sudden Stratospheric Warmings

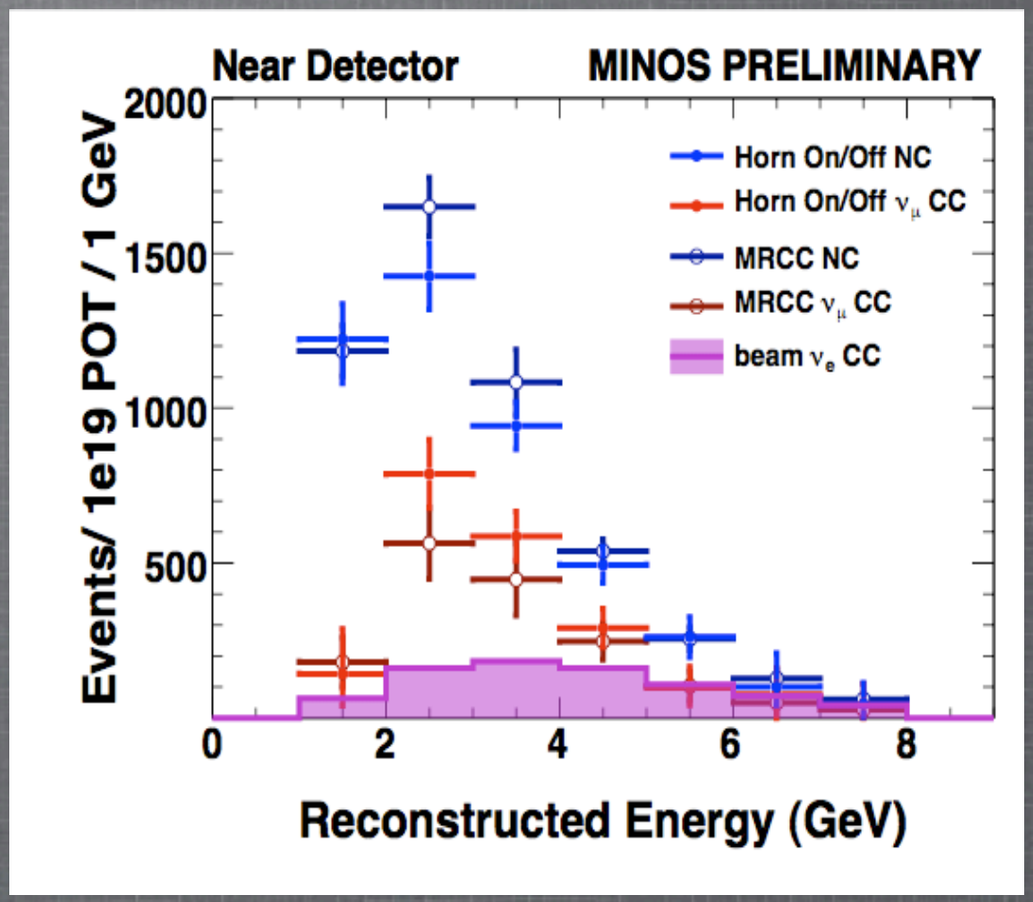


- There is a strong correlation between the high energy cosmic ray rate and temperature changes in the upper atmosphere.
- The MINOS FD observers a large cosmic muons rate and can measure these percent-level changes in rate.

- SSWs have been tracked using balloon measurements, rocket soundings, LIDAR, airborn and satellite observations. MINOS now provides another new tool with which to observe these meteorological phenomena.

ν_e Data-Driven Background Studies





Estimate	Signal ν_e	Total BG	NC	ν_μ CC	Beam ν_e	ν_τ CC
Horn On/Off	12	42	29	8	3	2
MRCC	12	43	32	6	3	2

→ $\sin^2(2\theta_{23}) = 1.0$
$\Delta m^2_{32} = 2.4 \times 10^{-3}$ eV^2
$\sin^2(2\theta_{13}) = 0.15$
no matter effects
3.25×10^{20} POT

- Horn On/Off - constrain the relative ratios of NC and ν_μ CC background events in two different beam configurations.
- Muon removed hadron showers from ν_μ CC (MRCC).

QUESTIONS I HAVE

- Can someone remind me why the best fit value on the top (small) plot on slide 17 has sin2(2t) > 1? Is it just statistics? This plot was made with MC...
- Will the NC result be redone with our latest values of dm2 and sin2(2θ)?
- Should I mention the Horn 1 problem?
- Can I mention the Nature article submission?

NOTE:

- I intend to add more backup slides, but if you have any specific suggestions, please let me know!